CLEAN COAL RESEARCH PROGRAM

United States Department of Energy | Office of Fossil Energy

ADVANCED TURBINES
TECHNOLOGY PROGRAM PLAN

JANUARY 2013

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CHAPTER 1: OVERVIEW

1.1 INTRODUCTION

The Department of Energy's (DOE) Advanced Turbines program is conducted under the Clean Coal Research Program (CCRP). DOE's overarching mission is to increase the energy independence of the United States and to advance U.S. national and economic security. To that end, the DOE Office of Fossil Energy (FE) has been charged with ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. As a component of that effort, the CCRP—administered by the Office of Clean Coal and implemented by the National Energy Technology Laboratory (NETL)—is engaged in research, development, and demonstration (RD&D) activities to create technology and technology-based policy options for public benefit. The CCRP is designed to remove environmental concerns related to coal use by developing a portfolio of innovative technologies, including those for carbon capture and storage (CCS). The CCRP comprises two major program areas: CCS and Power Systems and CCS Demonstrations. The CCS and Power Systems program area is described in more detail below. The CCS Demonstrations program area includes three key subprograms: Clean Coal Power Initiative, FutureGen 2.0, and Industrial Carbon Capture and Storage. The technology advancements resulting from the CCS and Power Systems program area are complemented by the CCS Demonstrations program area, which provides a platform to demonstrate advanced coal-based power generation and industrial technologies at commercial scale through cost-shared partnerships between the Government and industry.

While it has always been an influential component of CCS research, recently DOE has increased its focus on carbon utilization to reflect the growing importance of developing beneficial uses for carbon dioxide (CO_2). At this time, the most significant utilization opportunity for CO_2 is in enhanced oil recovery (EOR) operations. The CO_2 captured from power plants or other large industrial facilities can be injected into existing oil reservoirs. The injected CO_2 helps to dramatically increase the productivity of previously depleted wells—creating jobs, reducing America's foreign oil imports, and thus increasing energy independence. Simultaneously, the CO_2 generated from power production is stored permanently and safely. The CCRP is gathering the data, building the knowledge base, and developing the advanced technology platforms needed to prove that CCS can be a viable strategy for reducing greenhouse gas emissions to the atmosphere, thus ensuring that coal remains available to power a sustainable economy. Program efforts have positioned the United States as the global leader in clean coal technologies.

This document serves as a program plan for NETL's Advanced Turbines research and development (R&D) effort, which is conducted under the CCRP's CCS and Power Systems program area. The program plan describes the Advanced Turbines R&D efforts in 2013 and beyond. Program planning is a strategic process that helps an organization envision the future; build on known needs and capabilities; create a shared understanding of program challenges, risks, and potential benefits; and develop strategies to overcome the challenges and risks, and realize the benefits. The result of this process is a technology program plan that identifies performance targets, milestones for meeting these targets, and a technology pathway to optimize R&D activities. The relationship of the Advanced Turbines program[1] to the CCS and Power Systems program area is described in the next section.

1 Although Advanced Turbines is a Technology Area within the Advanced Energy Systems subprogram, it represents a program of research designed to help meet DOE goals. Thus, throughout this document the term Advanced Turbines program is used interchangeably with Advanced Turbines Technology Area.

1.2 CCS AND POWER SYSTEMS PROGRAM AREA

The CCS and Power Systems program area conducts and supports long-term, high-risk R&D to significantly reduce fossil fuel power-plant emissions (including CO_2) and substantially improve efficiency, leading to viable, near-zero-emissions fossil fuel energy systems. The success of NETL research and related program activities will enable CCS technologies to overcome economic, social, and technical challenges including cost-effective CO_2 capture, compression, transport, and storage through successful CCS integration with power-generation systems; effective CO_2 monitoring and verification; permanence of underground CO_2 storage; and public acceptance. The overall program consists of four subprograms: Advanced Energy Systems (AES), Carbon Capture, Carbon Storage, and Crosscutting Research (see Figure 1-1). These four subprograms are further divided into numerous Technology Areas. In several instances, the individual Technology Areas are further subdivided into key technologies. Advanced Turbines is part of the Advanced Energy Systems subprogram.

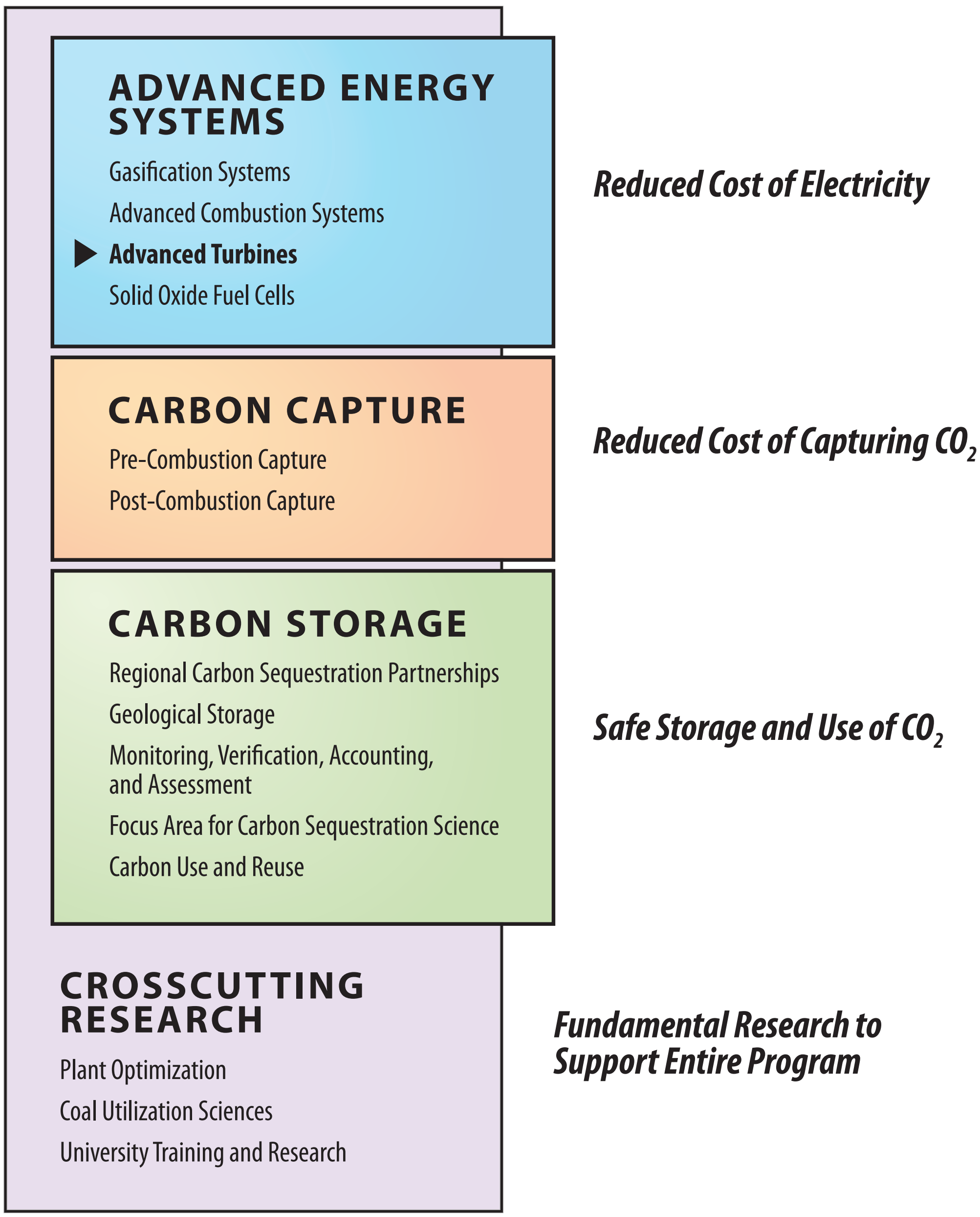

Figure 1-1. CCS and Power Systems Subprograms

The ***Advanced Energy Systems subprogram*** is developing a new generation of clean fossil fuel-based power systems capable of producing affordable electric power while significantly reducing CO_2 emissions. This new generation of technologies will essentially be able to overcome potential environmental barriers and meet any projected environmental emission standards. A key aspect of the Advanced Energy Systems subprogram is targeted at improving overall thermal efficiency, including the capture system, which will be reflected in affordable CO_2 capture and reduced cost of electricity (COE). The Advanced Energy Systems subprogram consists of four Technology Areas as described below and shown in Figure 1-2:

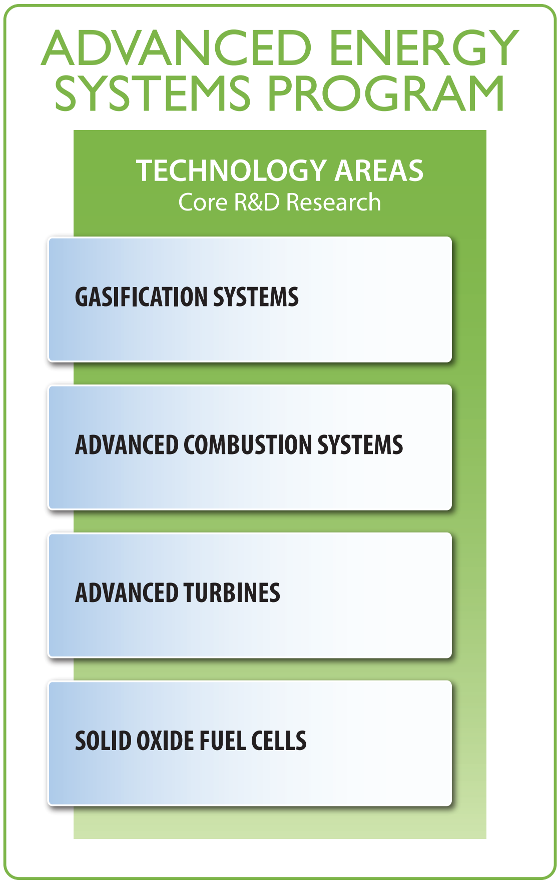

Figure 1-2. AES Subprogram Technology Areas

- ***Gasification Systems*** research to convert coal into clean high-hydrogen synthesis gas (syngas) that can in-turn be converted into electricity with over 90 percent CCS.
- ***Advanced Combustion Systems*** research that is focused on new high-temperature materials and the continued development of oxy-combustion technologies.
- ***Advanced Turbines*** research, focused on developing advanced technology for the integral electricity-generating component for both gasification and advanced combustion-based clean energy plants fueled with coal by providing advanced hydrogen-fueled turbines, supercritical CO_2-based power cycles and advanced steam turbines.
- ***Solid Oxide Fuel Cells*** research is focused on developing low-cost, highly efficient solid oxide fuel cell power systems that are capable of simultaneously producing electric power from coal with carbon capture when integrated with coal gasification.

The ***Carbon Capture subprogram*** is focused on the development of post-combustion and pre-combustion CO_2 capture technologies for new and existing power plants. Post-combustion CO_2 capture technology is applicable to conventional combustion-based power plants, while pre-combustion CO_2 capture is applicable to gasification-based systems. In both cases, R&D is underway to develop solvent-, sorbent-, and membrane-based capture technologies.

The ***Carbon Storage subprogram*** advances safe, cost-effective, permanent geologic storage of CO_2. The technologies developed and large-volume injection tests conducted through this subprogram will be used to benefit the existing and future fleet of fossil fuel power-generating facilities by developing tools to increase our understanding of geologic reservoirs appropriate for CO_2 storage and the behavior of CO_2 in the subsurface.

The ***Crosscutting Research subprogram*** serves as a bridge between basic and applied research by fostering the R&D of instrumentation, sensors, and controls targeted at enhancing the availability and reducing the costs of advanced power systems. This subprogram also develops computation, simulation, and modeling tools focused on optimizing plant design and shortening developmental timelines, as well as other crosscutting issues, including plant optimization technologies, environmental and technical/economic analyses, coal technology export, and integrated program support.

The CCS and Power Systems program area is pursuing three categories of CCS and related technologies referred to as 1st-Generation, 2nd-Generation, and Transformational. These categories are defined in Figure 1-3.

1st-Generation Technologies—include technology components that are being demonstrated or that are commercially available.

2nd-Generation Technologies—include technology components currently in R&D that will be ready for demonstration in the 2020–2025 timeframe.

Transformational Technologies—include technology components that are in the early stage of development or are conceptual that offer the potential for improvements in cost and performance beyond those expected from 2nd-Generation technologies. The development and scaleup of these "Transformational" technologies are expected to occur in the 2016–2030 timeframe, and demonstration projects are expected to be initiated in the 2030–2035 time period.

Figure 1-3. CCS Technology Category Definitions

1.3 THE RD&D PROCESS

The research, development, and demonstration of advanced fossil fuel power-generation technologies follows a sequential progression of steps toward making the technology available for commercial deployment, from early analytic study through pre-commercial demonstration. Planning the RD&D includes estimating when funding opportunity announcements (FOAs) will be required, assessing the progress of ongoing projects, and estimating the costs to determine budget requirements.

1.3.1 TECHNOLOGY READINESS LEVELS

The Technology Readiness Level (TRL) concept was adopted by the National Aeronautics and Space Administration (NASA) to help guide the RD&D process. TRLs provide an assessment of technology development progress on the path to meet the final performance specifications. The typical technology development process spans multiple years and incrementally increases scale and system integration until final-scale testing is successfully completed. The TRL methodology is defined as a "systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology."[2] Appendix A includes a table of TRLs as defined by DOE Office of Fossil Energy.

The TRL score for a technology is established based upon the scale, degree of system integration, and test environment in which the technology has been successfully demonstrated. Figure 1-4 provides a schematic outlining the relationship of those characteristics to the nine TRLs.

2 Mankins, J., Technology Readiness Level White Paper, 1995, rev. 2004, Accessed September 2010. http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf

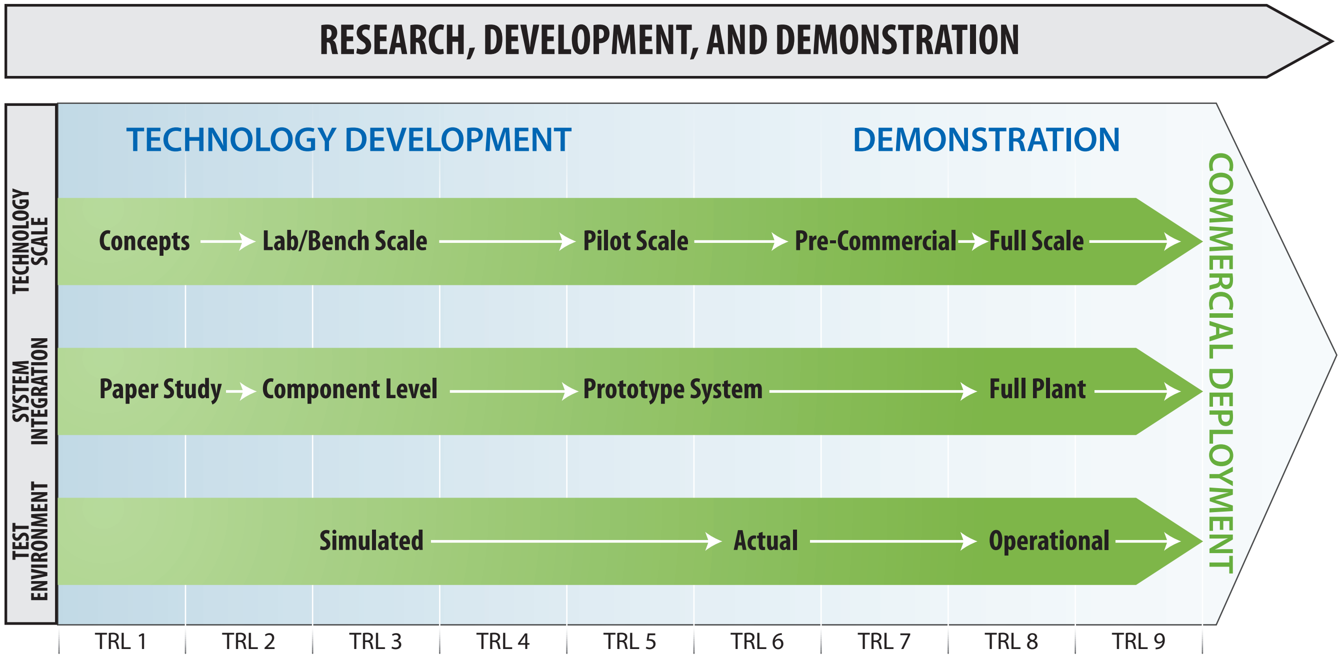

Figure 1-4. Technology Readiness Level—Relationship to Scale, Degree of Integration, and Test Environment

The scale of a technology is the size of the system relative to the final scale of the application, which in this case is a full-scale commercial power-production facility. As RD&D progresses, the scale of the tests increases incrementally from lab/bench scale, to pilot scale, to pre-commercial scale, to full-commercial scale. The degree of system integration considers the scope of the technology under development within a particular research effort. Early research is performed on components of the final system, a prototype system integrates multiple components for testing, and a demonstration test of the technology is fully integrated into a plant environment. The test environment considers the nature of the inputs and outputs to any component or system under development. At small scales in a laboratory setting it is necessary to be able to simulate a relevant test environment by using simulated heat and materials streams, such as simulated flue gas or electric heaters. As RD&D progresses in scale and system integration, it is necessary to move from simulated inputs and outputs to the actual environment (e.g., actual flue gas, actual syngas, and actual heat integration) to validate the technology. At full scale and full plant integration, the test environment must also include the full range of operational conditions (e.g., startup and turndown).

1.3.2 RD&D RISK AND COST PROGRESSION

As the test scale increases, the duration and cost of the projects increase, but the probability of technical success also tends to increase. Given the high technical risk at smaller scales, there will often be several similar projects that are simultaneously supported by the program. On the other hand, due to cost considerations, the largest projects are typically limited to one or two that are best-in-class. Figure 1-5 provides an overview of the scope of laboratory/bench-, pilot-, and demonstration-scale testing in terms of test length, cost, risk, and test conditions. In the TRL construct, “applied research” is considered to be equivalent to lab/bench-scale testing, “development” is carried out via pilot-scale field testing, and “large-scale testing” is the equivalent of demonstration-scale testing. The CCS and Power Systems program area encompasses the lab/bench-scale and pilot-scale field testing stages and readies the technologies for demonstration-scale testing.

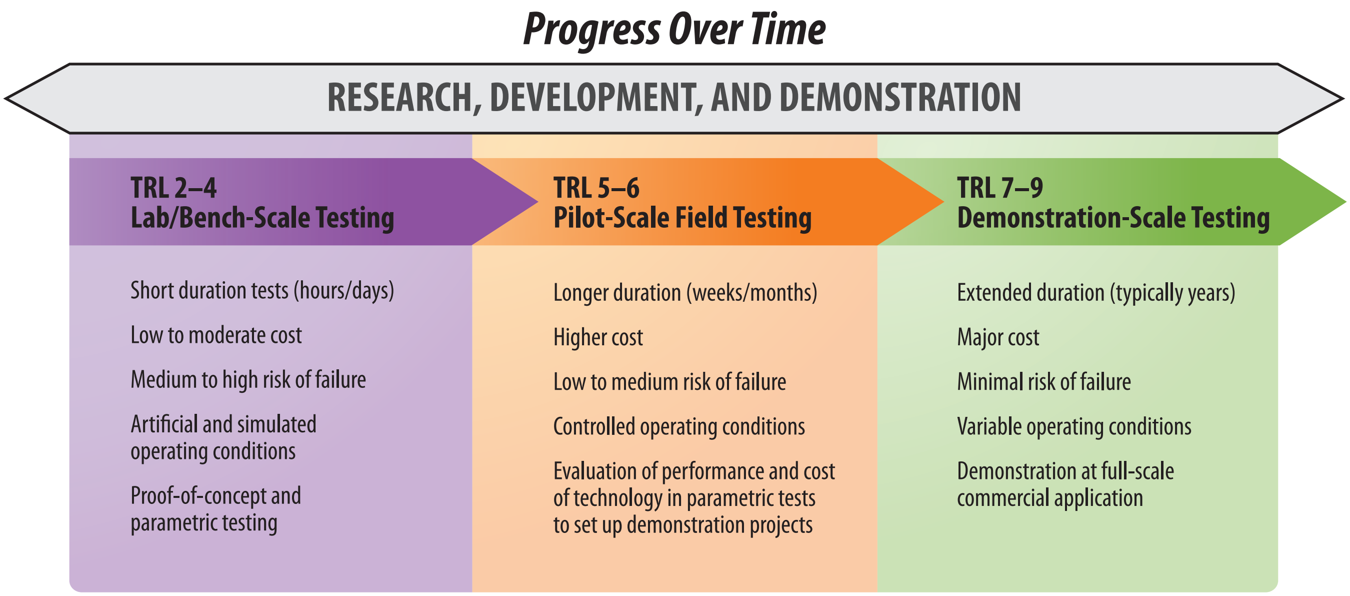

Figure 1-5. Summary of Characteristics at Different Development Scales

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CHAPTER 2: ADVANCED TURBINES PROGRAM

2.1 INTRODUCTION

The Advanced Turbines Technology Area supports four key technologies that will build technology leadership for sustained jobs, and enable clean energy to support the U.S. economy and global ecology: (1) Hydrogen Turbines, (2) Supercritical CO_2 Power Cycles, (3) Advanced Oxy-Fuel Turbine, and (4) Advanced Steam Turbines. The research focus for each of these technologies is depicted in Figure 2-1. 2nd-Generation research is or will be conducted on hydrogen (H_2) turbines (2,650 °F), and oxy-fuel turbines. Transformational research will be conducted on advanced hydrogen turbines (3,100 °F), supercritical CO_2 power cycles, and advanced steam turbines. Some background information on the rational for advanced turbine R&D is provided in the subsequent sections, with additional details provided in *Chapter 4: Technical Plan*.

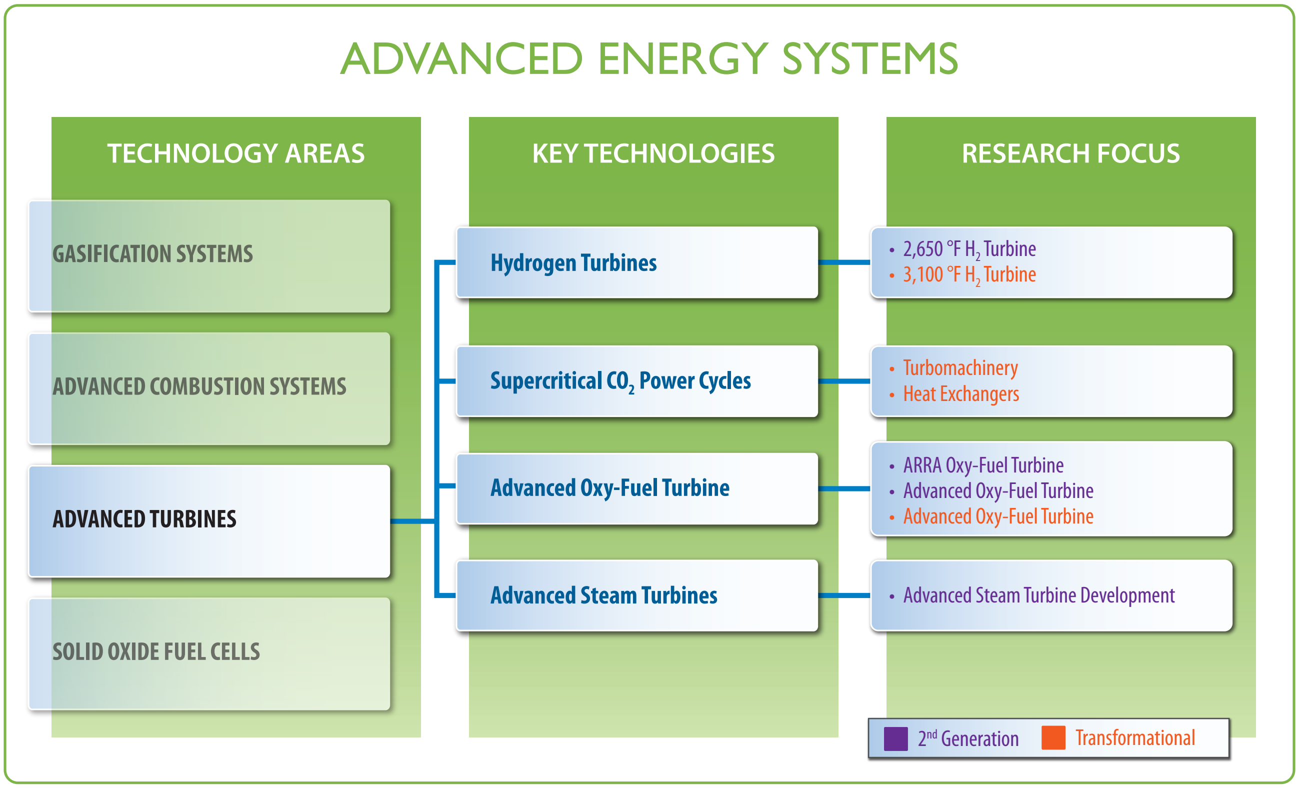

Figure 2-1. Key Technologies and Associated Research Focus in Advanced Turbines

2.2 BACKGROUND

Turbines in power plants convert heat energy to mechanical energy by expanding a hot, compressed working fluid through a series of airfoils. Utility-scale combustion turbines, as shown in Figure 2-2, draw in air, compress it (left), send it to a combustor where it is combusted with a fossil fuel (to include natural gas or coal derived synthesis gas or hydrogen)(center), and then expand the combustion gases through the airfoils (right). The exhaust gas of a combustion turbine is very hot and can be used to preheat combustion air in a simple cycle application, or generate steam in a heat recovery steam generator for a steam turbine in a combined cycle application. The efficiency of combustion turbines has steadily increased as advanced technologies have provided manufacturers with the ability to produce highly advanced turbines that operate at very high temperatures.

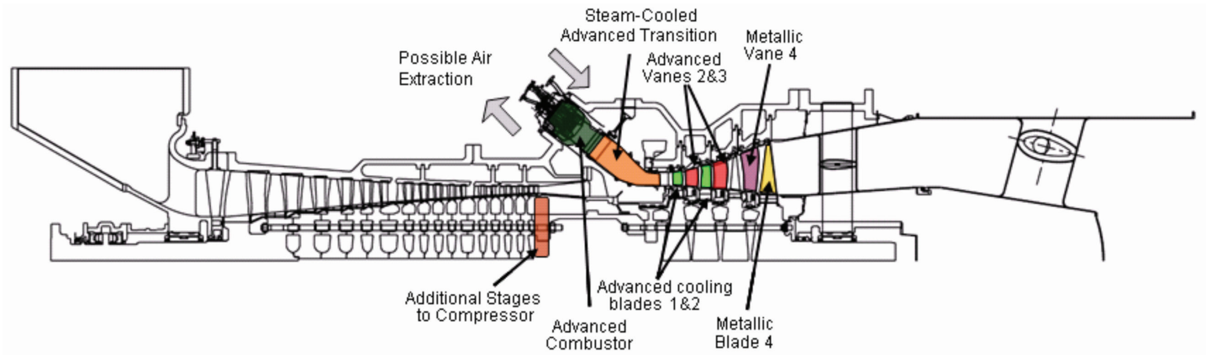

Figure 2-2. Advanced Hydrogen Turbine

Turbines represent the backbone of fossil fuel electric power generation. Steam turbines exist in virtually every conventional power plant and natural-gas-fueled combustion turbines are providing over one-fourth of the electricity in the United States. When considering that an increasing share of the nation's fossil fuel generating capacity is supplied by natural gas and the low price of this readily available fuel, the combustion turbine power plant represents the most cost-effective and efficient fossil fuel power cycle. Fortunately, the same advanced turbine technology for natural-gas-fueled machines with modifications that reduce machine efficiency can be deployed for coal-based advanced integrated gasification combined cycle (IGCC) with hydrogen-fueled turbines and low-cost carbon capture.

Although the majority of deployed turbines are air-fired combustion turbines or expansion turbines with a steam working fluid, turbines are very versatile and can be designed to operate in an oxygen fired configuration and with working fluids other than steam. Oxy-fuel turbines have a working fluid that contains mostly CO_2 and water. The water can be condensed out of the turbine exhaust, leaving an almost pure stream of CO_2 that can be stored or utilized for EOR applications. Novel advanced turbines that utilize supercritical CO_2 as the working fluid can be coupled with any heat source and provide a low cost advanced fossil fuel combustion option with carbon capture. The limited commercial availability of these alternate turbine configurations makes them particularly high risk, while the improvements they offer could be significant.

The Advanced Turbines program at NETL is focused on R&D activities to develop technologies that will accelerate turbine performance and efficiency beyond current state-of-the-art and reduce the risk to market for novel and advanced turbine-based power cycles.

2.3 RECENT R&D ACTIVITIES

Advanced turbine development is undertaken in two parts: (1) fundamental research to address gaps in the knowledge base for turbine advancement and (2) applied development that is focused on building components that utilize the latest cutting-edge materials and technology to demonstrate feasibility in real-world conditions.

To accomplish this, the Advanced Turbines program is organized into three functional areas: Hydrogen Turbine Research, University Turbine Systems Research (UTSR), and Advanced Research. These three areas directly support the overall goals for the Advanced Turbines program by addressing significant scientific and engineering challenges associated with meeting increasing demands on turbine technology when using hydrogen fuels derived from coal. Hydrogen turbine research is lead by U.S. industry leaders—General Electric and Siemens—in large-frame power-generation turbines for IGCC. Their work is directly supported by the applied research of the UTSR program. Research conducted through the UTSR program is closely coupled to DOE goals and industries needs in the applied areas of hydrogen combustion, materials, heat transfer, and aerodynamics. The Advanced Research functional area supports the development of new and innovative manufacturing techniques and addresses fundamental understanding in materials and combustion research.

HYDROGEN TURBINE RESEARCH

Developing advanced gas turbines fueled with pure hydrogen in coal-based IGCC applications that capture 90 percent of the plant carbon offers the single largest impact for efficiency and cost of electricity improvements as compared to other technologies being developed. System studies confirm that the Advanced Turbines program can meet and exceed established program goals assuming the appropriate technology can be developed and deployed.

The Hydrogen Turbines functional area focus is on developing a hydrogen-fueled turbine with the following nominal conditions: 2,650 °F turbine inlet temperature, pressure ratio of 24, and nominal inlet airflow of 4.6 million pounds per hour. The program aims to develop this turbine by focusing on specific research areas to include: low nitrogen oxide (NO_x) hydrogen combustion systems, increasing turbine inlet temperature, reducing interstage leakage, minimizing cooling requirements and cooling flows, advanced materials, and advanced airfoil designs. Key technologies, components, and subsystems being developed in this program include:

- Low NO_x premixed hydrogen combustors for large-frame turbines
- Material systems and architectures for base materials and coatings that allow higher temperature operation
- Stationary and rotating airfoils with superior aerodynamics, strength, and cooling technology
- Revolutionary gas turbine components and designs

UNIVERSITY TURBINE SYSTEMS RESEARCH

Since the inception of the DOE turbine program, the UTSR program has sought to provide the underlying scientific research to develop advanced turbines and turbine-based systems in support of DOE's turbine program goals. The success of the UTSR program has been made possible by an informal network of universities, the collaborating gas turbine industry, and the DOE turbine program—all of which are facilitated by an annual UTSR workshop. UTSR also offers a Gas Turbine Industrial Fellowship funded by sponsoring gas turbine manufacturers. This fellowship has helped to facilitate the transition of the best students from academia to the gas turbine industry, thereby helping to maintain U.S. leadership in this important area of technology. UTSR projects are established through an annual competitive solicitation open to all U.S. universities. Solicitation R&D topics are established in response to DOE program goals and given specific focus through communications with the gas turbine industry.

ADVANCED RESEARCH

Advanced research under the turbine program is conducted with corporate partners, small businesses, and Government laboratories to advance the goals of the Advanced Turbines program. The selected institutions are uniquely qualified to perform research and address specific areas that complement ongoing efforts to develop advanced turbine technology. The program is also augmented by a portfolio of Small Business Innovation Research projects that are organized under the Advanced Research functional area.

A list of active (as of October 2012) Advanced Turbines projects, associated TRL scores, and project descriptions is provided in Appendix B.

CHAPTER 3: GOALS AND BENEFITS

3.1 GOALS

The goals of the Advanced Turbines program support the energy goals established by the Administration, DOE, FE, and the CCRP. The priorities, mission, goals, and targets of each of these entities are summarized in Appendix C.

3.1.1 CCRP GOALS

Currently, the CCRP is pursuing the demonstration of 1st-Generation CCS technologies with existing and new power plants and industrial facilities using a range of capture alternatives and storing CO_2 in a variety of geologic formations. In parallel, to drive down the costs of implementing CCS, the CCRP is pursuing RD&D to decrease the COE and capture costs and increase base power-plant efficiency, thereby reducing the amount of CO_2 that has to be captured and stored per unit of electricity generated. FE is developing a portfolio of technology options to enable this country to continue to benefit from using our secure and affordable coal resources. The challenge is to help position the economy to remain competitive, while reducing carbon emissions.

There are a number of technical and economic challenges that must be overcome before cost-effective CCS technologies can be implemented. The experience gained from the sponsored demonstration projects focused on state-of-the-art (1st Generation) CCS systems and technologies will be a critical step toward advancing the technical, economic, and environmental performance of 2nd-Generation and Transformational systems and technologies for future deployment. In addition, the core RD&D projects being pursued by the CCRP leverage public and private partnerships to support the goal of broad, cost-effective CCS deployment. The following long-term performance goals have been established for the CCRP:

- Develop 2nd-Generation technologies that:
  - Are ready for demonstration in the 2020–2025 timeframe (with commercial deployment beginning in 2025)
  - Cost less than $40/tonne of CO_2 captured
- Develop Transformational technologies that:
  - Are ready for demonstration in the 2030–2035 timeframe (with commercial deployment beginning in 2035)
  - Cost less than $10/tonne of CO_2 captured

The planning necessary to implement the above goals and targets is well underway and the pace of activities is increasing. The path ahead with respect to advancing CCS technologies, particularly at scale, is very challenging given today's economic risk-averse climate and that no regulatory framework is envisioned in the near term for supporting carbon management. These conditions have caused DOE/FE to explore a strategy with increased focus on carbon utilization as a means of reducing financial risk. This strategy benefits from FE's investment in the beneficial utilization of CO_2 for commercial purposes, particularly through the development of next-generation CO_2 injection/EOR technology, with the objective of creating jobs and increasing energy independence. Carbon dioxide injection/EOR is a specific market-based utilization strategy that will positively impact domestic oil production and economical CO_2 capture and storage.

3.1.2 ADVANCED ENERGY SYSTEMS STRATEGIC GOALS

The AES program supports achievement of the CCRP goals by developing and demonstrating advanced, efficient technologies that produce ultraclean (near-zero emissions, including CO_2), low-cost energy with low water use. In support of those overall goals are the specific cost and performance goals for 2025 and 2035 described in the following sections and summarized in Table 3-1.

Table 3-1. **Market-Based R&D Goals for Advanced Coal Power Systems**

	Goals (for nth-of-a-kind plants)		Performance Combinations that Meet Goals	
R&D Portfolio Pathway	*Cost of Captured CO_2, $/tonne*[1]	*COE Reduction*[2]	*Efficiency (HHV)*	*Capital/O&M Reduction*[3]
2nd-Generation R&D Goals for Commercial Deployment of Coal Power in 2025[4]				
In 2025, EOR revenues will be required for 2nd-Generation coal power to compete with natural gas combined cycle and nuclear in absence of a regulation-based cost for carbon emissions.				
Greenfield Advanced Ultra-Supercritical (A-USC) Pulverized Coal (PC) with CCS	40	20%	37%	13%
Greenfield Oxy-Combustion PC with CCS	40	20%	35%	18%
Greenfield Advanced IGCC with CCS	≤40	≥20%	40%	18%
Retrofit of Existing PC with CCS	45	n/a		
Transformational R&D Goals for Commercial Deployment of Coal Power in 2035[4]				
Beyond 2035, Transformational R&D and a regulation-based cost for carbon emissions will enable coal power to compete with natural gas combined cycle and nuclear without EOR revenues.				
New Plant with CCS—Higher Efficiency Path	<10[5]	40%	56%	0%
New Plant with CCS—Lower Cost Path	<10[5]	40%	43%	27%
Retrofit of Existing PC with CCS	30	≥40%	n/a	
Transformational pathways could feature advanced gasifiers, advanced CO_2 capture, 3,100 °F gas turbines, supercritical CO_2 cycles, pulse combustion, direct power extraction, pressurized oxy-combustion, chemical looping, and solid oxide fuel cells.				

NOTES:

(1) Assumes 90 percent carbon capture. First-year costs expressed in 2011 dollars, including compression to 2,215 pounds per square inch absolute (psia) but excluding CO_2 transport and storage (T&S) costs. The listed values do not reflect a cost for carbon emissions, which would make them lower. For greenfield (new) plants, the cost is relative to a 2nd-Generation ultra-supercritical PC plant without carbon capture. For comparison, the nth-of-a-kind cost of capturing CO_2 from today's IGCC plant, compared to today's supercritical PC without carbon capture, is about $60/tonne. For retrofits, the cost is relative to the existing plant without capture, represented here as a 2011 state-of-the-art subcritical PC plant with flue gas desulfurization and selective catalytic reduction. The cost of capturing CO_2 via retrofits will vary widely based on the characteristics of the existing plant such as its capacity, heat rate, and emissions control equipment. The nth-of-a-kind cost of capture for retrofitting the representative PC plant described above (a favorable retrofit target) using today's CO_2 capture technology would be about $60/tonne. (In contrast, today's first-of-a-kind cost of CO_2 capture for a new or existing coal plant is estimated to be $100–$140/tonne.)

(2) Relative to the first-year COE of today's state-of-the-art IGCC plant with 90 percent carbon capture operating on bituminous coal, which is currently estimated at $133/MWh. For comparison, the first-year COE of today's supercritical PC with carbon capture is estimated to be $137/MWh. Values are expressed in 2011 dollars. They include compression to 2,215 psia but exclude CO_2 T&S costs and CO_2 EOR revenues. However, CO_2 T&S costs were considered, as appropriate, when competing against other power-generation options in the market-based goals analysis.

(3) Cost reduction is relative to today's IGCC with carbon capture. Total reduction is comprised of reductions in capital charges, fixed operating and maintenance (O&M) and non-fuel variable O&M costs per million British thermal unit (Btu) (higher heating value [HHV]) of fuel input. Cost reductions accrue from lower equipment and operational costs, availability improvements, and a transition from high-risk to conventional financing. The ability to secure a conventional finance structure is assumed to result from lowering technical risk via commercial demonstrations.

(4) 2nd-Generation technologies will be ready for large-scale testing in 2020, leading to commercial deployment by 2025 and attainment of nth-of-a-kind performance consistent with R&D goals by 2030. Transformational technologies will be ready for large-scale testing in 2030, leading to initial commercial deployment in 2035 and attainment of nth-of-a-kind performance consistent with R&D goals by 2040.

(5) Cost of captured CO_2 ranges from $5 to $7/tonne for the cost reductions and efficiencies noted.

2ND-GENERATION R&D GOALS

Complete the R&D needed to prepare 2nd-Generation gasification and advanced combustion technologies—that show the ability to produce low-cost, ultraclean energy with near-zero emissions—for demonstration-scale testing (leading to commercial deployment beginning in 2025). These technologies will reduce the cost to produce energy—power with carbon capture, fuels/chemicals, or multiple products (i.e., polygeneration). Cost and performance improvements will be driven by advancements in technologies being developed in the Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Crosscutting Research, and Carbon Capture R&D programs. As shown in Table 3-1, integrating the 2nd-Generation technologies has the potential to produce near-zero-emissions power with reductions in capital and O&M costs of 13–18 percent and plant efficiency of 35–40 percent. This is equivalent to a COE reduction of greater than 20 percent and a capture cost of less than $40/tonne of CO_2.

TRANSFORMATIONAL R&D GOALS

Successfully develop Transformational technologies with CCS that produce low-cost, near-zero-emissions energy generation and are ready for demonstration-scale testing leading to commercial deployment in 2035. These technologies will reduce the cost to produce energy—power with carbon capture, fuels/chemicals, or multiple products (i.e., polygeneration). For power production, maturing technologies continue to show anticipated cost and performance improvements that will be driven by advancements in technologies being developed in the Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Solid Oxide Fuel Cells, Crosscutting Research, and Carbon Capture R&D programs, which will result in near-zero-emissions power production with capital and O&M cost reductions of 0–27 percent and plant efficiency of 43–56 percent. This is equivalent to a COE reduction of greater than 40 percent and a capture cost of less than \$10/tonne of CO_2.

3.1.3 ADVANCED TURBINES GOALS

The Advanced Turbines program supports the AES goals through the development of advanced turbines and power cycles. As noted previously, the AES goals are expected to be achieved through the integration of technologies developed as part of the Gasification Systems, Advanced Combustion Systems, Advanced Turbines, Solid Oxide Fuel Cells, Crosscutting Research, and Carbon Capture R&D programs. Given that the CCRP/AES long-term goal is to reduce the cost of CO_2 capture from current levels of approximately \$60/tonne to less than \$10/tonne, advanced turbine system technologies are targeted to contribute 60 percent of the long-term cost reduction goal for an IGCC and 20 percent of the long-term cost reduction goal for combustion systems.

3.2 BENEFITS

A DOE investment in advanced turbine technology is a compelling choice for low-carbon electric power generation. The turbine technology investment offers significant benefits across all of our nation's key energy resources including coal, natural gas, nuclear, and renewables. Additionally, the turbine technology investment also promotes positive outcomes in U.S. technology leadership, global competitiveness, a cleaner environment, and domestic job growth. Such an investment will:

- Supply the next generation of combustion turbine technology applicable to both coal and natural gas with or without carbon capture for higher efficiency and lower cost.
- Demonstrate the building blocks of an integrated and modular EOR power system providing CO_2, power, and water for remote EOR opportunities.
- Develop new supercritical CO_2 turbomachinery for an advanced low-cost coal combustion option with carbon capture and other fossil-energy applications (the same turbomachinery will also benefit solar and nuclear power plant applications, and Department of Defense [DoD] propulsion applications).
- Develop next-generation steam turbine technology that will benefit the entire utility industry with higher efficiency and lower carbon capture costs.

2nd-Generation and Transformational advanced combustion turbines have powerful benefits, in that they are capable of higher efficiencies, lower COE, and can be used in many applications and across all fuels. These turbines are applicable to advanced coal- and natural-gas-fueled systems and are significant assets in many strategies for reducing the carbon footprint of the electric power sector. Similar turbine technology using pure oxygen instead of air offers a modular power system that is capable of a competitive cost of electricity and can produce CO_2 and water for domestic EOR activities.

Advanced turbine power cycles with supercritical CO_2 as the working fluid will form the building block for more efficient electric power generation that is carbon free. These Transformational power cycles offer significant performance advancement with reduced cost and options for 100 percent carbon capture. When the advanced cycle is configured as a supercritical power cycle, employing CO_2 as the working fluid and advanced heat exchangers, a lower cost coal combustion option is possible. The same turbomachinery for this cycle can also directly benefit utility-scale solar and nuclear power production and a bottoming cycle for simple cycle gas turbines, as well as many DoD propulsion and power applications.

The United States is a global leader in gas turbine technology; however, without continued Federal research investment, this leadership will be lost. This loss will jeopardize the domestic job base, domestic market, and significant U.S. export market for this technology. Advanced turbine technology investment is needed to meet demands for clean energy and to allow the United States to remain competitive with ongoing foreign investment in turbine R&D. The second-tier advanced technology and manufacturing sector that supports the turbine industry and the active university base that is engaging and developing the next generation of turbine experts are also at risk. Without a robust Federal investment in advanced turbine technology we lose options for clean energy production while placing a significant domestic industry in jeopardy.

It is important to recognize that the limited commercial availability of Transformational turbine configurations and cycles make them particularly high-risk technologies. The Department's Advanced Turbines program at NETL is focused on R&D activities to develop technologies that will accelerate turbine performance and efficiency beyond current state-of-the-art and reduce the risk to market for novel and advanced turbine power cycles. This research is essential to strengthen the United States' position as a global leader in advanced turbine technology development.

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CHAPTER 4: TECHNICAL PLAN

4.1 INTRODUCTION

The Advanced Turbines Technology Area supports four key technology pathways during the 2013–2030 time period. These technologies bring together a mix of turbine-based technology solutions that have significant relevance in the current and future market place. These pathways are designed to advance clean, low-cost, coal-based power production—and at the same time—take advantage of all fossil fuel opportunities.

The four key technologies include:

- Hydrogen Turbines
- Supercritical CO_2 Power Cycles
- Advanced Oxy-Fuel Turbine
- Advanced Steam Turbines

Each of these key technology pathways will develop technologies to overcome R&D challenges in the following focus areas:

- High turbine inlet temperatures:
  - 3,100 °F for fossil fuel turbines
  - 2,000–2,500 °F for oxy-fuel turbines
  - 1,600 °F for CO_2-based indirect cycles and 2,600 °F (and higher) for direct cycles
  - 1,400 °F for advanced steam turbines at 5,000 pounds per square inch (psi)
- Materials for high-temperature and high-load applications in challenging atmospheres
- Advanced airfoil cooling technology
- Low NO_x combustion of hydrogen, syngas and natural gas
- Pressure gain combustion
- New material system architectures
- Aerodynamic designs for highly loaded airfoils
- Sealing and leakage control

Presented in the subsequent sections are discussions on the four R&D pathways for the Advanced Turbines program. This discussion will include subsections on the key technology background, technology status, the R&D approach as well as benefits. Included in the benefits section is a discussion of the risks and mitigation strategies to realize these benefits.

4.2 HYDROGEN TURBINES

Advanced hydrogen turbines are an essential component of the IGCC power system with carbon capture. Realizing the benefits from developing advanced hydrogen turbines for IGCC will make carbon capture in coal-based electric power generation economically feasible through leveraging the market-based benefits of selling CO_2 for EOR applications. To realize these benefits and deploy coal-based IGCC power generation with carbon capture and utilization a robust investment in hydrogen turbine technology is required.

4.2.1 BACKGROUND

Gas turbines used in IGCC power plants have always been built on modified natural gas-fueled turbine platforms. These machines modified for IGCC applications typically compromise IGCC plant efficiency due to lower firing temperatures and lower power outputs. These deratings are made to accommodate the unique characteristics of the coal-derived fuel in the context of a machine designed for natural gas. This approach includes the machines at the Tampa Electric, Wabash River, Duke Energy Edwardsport, ELCOGAS Puertollano, and Nuon Power Buggenum IGCC power-generation facilities. The most advanced machine for a coal application will only have a fraction of the performance of the most advanced machine for natural gas. The derating that occurs is mostly driven by moisture content, space velocities, throughput, and torque limits. There is little evidence to suggest that the derating approach will change; and new IGCC plants that are built will use the most advanced gas turbine available, designed for natural gas and derated for the coal application. Fortunately, the vast majority of technology developments that lead to better performance are indifferent to the fuel (coal-based hydrogen or natural gas).

The DOE Energy Information Administration (EIA) is predicting a significant build out in the natural gas-fueled generation capacity. For the period of 2009–2035, EIA predicts 220 GW of new-generation capacity will be added in the United States. Due to the projected low and stable price of natural gas, 62 percent of this new capacity, 135 GW, will be powered by gas turbine technology. A similar expansion in electricity demand on the order of 2,500 GW is expected to occur worldwide over the same timeframe. Likewise approximately 20 percent of this demand, or 550 GW, is expected to be met through gas turbine technology. This projected demand should be a driver in itself to motivate U.S. Government investment so as to maintain leadership in the most advanced turbine technology possible. A significant portion of this capacity addition, on the order of 25 percent, is projected to be renewable, like wind and solar. Renewable additions pose technical challenges to the nation's grid when accommodating the diurnal nature of these systems. Power-generation systems that can load follow, like gas turbines, are particularly challenged to accommodate this changing characteristic of the grid. In general the technology issues brought about by this challenge fall into the following categories: (1) fast load ramp with emissions compliance, (2) peaking start, (3) turndown, (4) part load efficiency, and (5) power augmentation.

For the most part this shift from coal-fueled to natural gas-fueled has been brought about by, the advent of horizontal drilling and hydraulic fracturing making natural gas abundant and inexpensive. This market-based force has shifted the playing field from the addition of coal-based generating capacity toward the addition of natural gas-based generating capacity.

Currently proposed regulatory rules for CO_2 emissions have raised a cautionary flag when considering the deployment of new coal-based generating capacity. These proposed rules have tied plant efficiency to a CO_2 emissions rate on a megawatt-hour basis and include a controlling floor set at a CO_2 per megawatt hour nominally equal to CO_2 emissions rate for current natural gas-fired combined cycle plants. Potential rules like these have forced turbine researchers for coal applications to consider even more advanced machines with even higher turbine inlet temperatures to increase efficiency and reduce the amount of CO_2 emissions per megawatt hour.

In summary, under current market conditions the goal of a high performance coal-based hydrogen-fueled turbine can be best reached by developing the most advanced technology in the areas of materials, cooling, heat transfer, manufacturing, aerodynamics, and machine design. Success in these areas will allow machines to be designed that have higher efficiencies and power output with lower emissions and lower cost. It is additionally beneficial that these advancements benefit machines for all fossil fuels including coal-based hydrogen and natural gas. With this approach, Government funding with a cost sharing commercial sector can push the technology in the context of a market pull currently driven by low natural gas prices. At the end of the day, the United States needs to maintain worldwide turbine technology leadership that can be applied to all fossil fuels, including coal as the market dictates.

4.2.2 TECHNICAL DISCUSSION

The subsequent discussion provides an overview of the technical development of the current hydrogen turbine projects as they progress toward the 2nd-Generation goal of hydrogen-fueled turbine with a nominal turbine inlet temperature of 2,650 °F. Also provided is a discussion of the technology that would be pursued in the Transformational goal for a hydrogen turbine with an inlet temperature of 3,100 °F.

2ND-GENERATION HYDROGEN TURBINE (2,650 °F)

The focus of the Hydrogen Turbine key technology is on developing a hydrogen-fueled turbine with the following nominal conditions: 2,650 °F turbine inlet temperature, pressure ratio of 24, and nominal inlet airflow of 4.6 million pounds per hour. The program aims to develop this turbine by focusing on specific research areas to include: low NO_x hydrogen combustion systems, increasing turbine inlet temperature, reducing interstage leakage, minimizing cooling requirements and cooling flows, advanced materials, and advanced airfoil designs. Key technologies, components, and subsystems being developed in this program include:

- Low NO_x premixed hydrogen combustors for large-frame turbines
- Material systems and architectures for base materials and coatings that allow higher temperature operation
- Stationary and rotating airfoils with superior aerodynamics, strength, and cooling technology
- Revolutionary gas turbine components and designs

Provided in the following sections is a discussion of progress toward these specific research areas.

High-Hydrogen Combustion—Increased firing temperature capabilities were achieved, culminating from full-scale combustion testing and advanced manufacturing trials for advanced hot gas component systems. Full-scale component tests have met relative efficiency targets at low levels of NO_x emissions at the required firing temperatures in a "pre-production" demonstration indicating that the key combustion components have achieved a level of maturity that will allow production in the near future.

1st-Generation Ceramic Matrix Composite Components—1st-Generation ceramic matrix composite hot gas path components have been installed, tested, and evaluated in a relevant field test environment. Additionally, multiple parts for ceramic matrix composite components of varying complexities have been assembled. Some of these parts are undergoing testing in commercial machines and others are still being evaluated in the laboratory.

Advanced Material Systems—An advanced material system (base alloy, bond coats, thermal barrier coatings, environmental barrier coatings, etc.) capable of surviving 2,650 °F IGCC/H_2 turbine operation has been successfully developed. Initial performance of the materials, validated through laboratory and rig-test campaigns, resulted in the optimum material sets/systems being identified. These material systems will move on for further qualification testing to assess degradation modes and durability issues.

Advanced Turbine Blade Core Technologies (manufacturing and cooling)—New technologies that enable the manufacture of previously impossible core designs have been developed. These cores have allowed aerodynamic and heat transfer designs of hot gas path components, such as highly convective internally cooled turbine blades. These advanced designs emphasize greater cooling efficiencies for higher firing temperatures, reduced cooling requirements, and increased efficiency in the turbine.

At the conclusion of Phase II many technologies will have received sufficient development that they will have graduated to field testing. It is anticipated that there will be several advanced components and technologies that will not be fully developed by the end of the current Phase II work. Some of these component systems will have relevance to the Transformational goal of 3,100 °F turbine inlet temperature. Some of these candidate systems could be pursued further under the hydrogen turbine Transformational pathway discussed in subsequent sections of this document. Presented in the following sections are some of the potential components and technologies that could be pursued in a hydrogen turbine with a 3,100 °F inlet temperature.

TRANSFORMATIONAL HYDROGEN TURBINE (3,100 °F)

The technologies that will enable the Transformational hydrogen turbine with a turbine inlet temperature of 3,100 °F build on successes from 2nd-Generation component research. New areas of focus have also been identified and will be pursued. A summary of the focus area for this key technology R&D is presented in the subsequent sections.

2nd-Generation Ceramic Matrix Composite Components—An additional campaign is required to realize production-ready technologies of the more complex ceramic matrix composite hot gas path components. Highly engineered ceramic matrix composite turbine components will remove large cooling air requirements and increase the output and efficiency of the IGCC plant while allowing for a relatively lighter rotor and a more aerodynamically efficient turbine stage.

Transformational Heat Transfer and Material Systems—Increased temperatures require continued optimization of the advanced cooling features and material systems for hot gas path components within a 3,100 °F gas turbine. Opportunity technologies include refractory alloys, advanced modular airfoil designs, and transpiration cooling. All technology platforms will be validated through laboratory and rig-test campaigns.

Full Compressor Redesign—Full compressor redesign will be needed to optimize system pressure ratio and operational stability so as to make possible increased firing temperatures and higher mass flows.

Advanced Transition—Design of advanced staging between the combustion and rotating turbine in order to take full advantage of higher firing temperatures while still enabling cost reductions and performance increases.

Pressure Gain Combustion—Constant volume combustion in the form of pulse deflagration, pulse detonation or continuous detonation has the potential to achieve 4–6 percent point efficiency improvement over constant pressure combustion characteristic of modern day advanced gas turbine engines. Efficiency gains are attained through a reduction in entropy production as a result of the pressure gain across the combustor. Current research initiatives will focus on combustion control strategies and fundamental understanding of pressure wave-flame interaction.

4.2.3 R&D APPROACH

The R&D approach provides an explanation, justification, and the details of what will be involved in the transition from the current 2nd-Generation hydrogen turbine program with a 2,650 °F turbine inlet temperature to the higher Transformational firing temperature of 3,100 °F, including the reasoning for not pursuing Phase III of the current program with Government funds.

CONCLUDING THE 2ND-GENERATION HYDROGEN TURBINE PROGRAM

Phase II of the current program has been very successful. Several technologies were developed and have been designed into components. Some of those components are undergoing field trials and will be incorporated in to existing commercially offered products or future product offerings. This is the case for both General Electric and Siemens. Based on the work completed in Phase II and the current state-of-the-art for gas turbines it is likely that both original equipment manufacturers (OEMs) could build a machine that would operate at 2,650 °F and deliver the performance predicted by existing system studies. However to achieve this predicted performance a turbine designed specifically for an IGCC application would need to be designed and built. This machine would have the mass flow, pressure ratio, and firing temperature characteristics described previously. Only then would the efficiency and cost reduction benefits be realized for IGCC with carbon capture.

Turbine OEMs require a considerable market-based deployment projection, on the order of 20 machines or more a year for several years, to design and build a specific machine. It is unlikely that this purpose-specific IGCC turbine would be built, given the fact that there are no market driven coal-based IGCC projects with CCS in the near or mid-term plans. Phase III—as a competitively awarded future phase of the current program—would require considerable Government cost-share investment, a matching private OEM investment, and a suitable clean coal project to pull this machine to fruition. The project would require clean coal funding to offset potential turbine risks. Give these market conditions and the cost to design and build a machine specifically for and IGCC application it is highly unlikely that a Phase III initiative (through an FOA) would be successful.

Based on this situation it is recommended that Phase III be delayed until a suitable market-based technology pull exists. In the meantime technologies developed through Phase II will mature and evolve in the market place through the inclusion of these technologies in machines designed and operated with natural gas. This is actually what is occurring now with certain Phase II technologies.

In summary, the recommended approach of not pursuing Phase III and concluding the 2nd-Generation hydrogen turbine development in a 2015 timeframe is sound. Much of the technology and many of the components required to achieve the 2nd-Generation goals have been demonstrated either in the lab or in commercial facilities. Technology not fully developed can mature under OEM direction until Phase III is pursued (in a 2020 timeframe) or become candidate technology for a new higher temperature Transformational program.

INITIATING TRANSFORMATIONAL HYDROGEN TURBINE DEVELOPMENT

To achieve the Transformational goals presented in this document gas turbines fueled with pure hydrogen and higher firing temperatures will be required. A firing temperature suitable to show considerable progress toward the Transformational goal for IGCC with CCS has been estimated to be 3,100 °F. This nominal turbine firing temperature, along with the benefits accrued through other AES programs, will work together to realize the Transformational performance of coal-based power generation.

The goal of this key technology pathway is to build an advanced turbine with a nominal first stage rotor inlet temperature of 3,100 °F for hydrogen-fueled applications. Like the current Phase II hydrogen program, the majority of the funding would be focused on applied fundamental research to realize the advanced components and systems that will allow for the high firing temperatures. The R&D would be initiated in 2015 with an FOA for work in three phases. Phase I—research, development, and implementation plan, would be a 18-month effort to identify key R&D areas, anticipated costs, schedules, and benefits. Phase I would deliver an R&D implementation plan and a business development plant for fossil-fueled combined cycle power plants. Phase I results could serve as a "go or no-go" decision point. Phase II would be the heart of the program and require most of the anticipated funding, initiating in 2017 and lasting for 10–12 years. This phase would focus on the development of advanced materials, new material architectures, advanced airfoil designs that allow high loading with advanced cooling techniques, advanced combustion technology to include pressure gain combustion with NO_x control, advanced compressor designs for higher pressure ratios, and interstage leakage control. There are additional advanced component designs that would be included in this machine to reach the advanced performance conditions. Taken together the technology developed through Phase II will allow for the design of a machine with a 3,100 °F turbine inlet temperature. Phase III can be considered a separate and additional competitively awarded FOA or included in the initial 2015 FOA. Phase III, initiated in a 2029 timeframe, would be focused on transitioning the components developed in Phase II into the design and manufacturing of a purpose-built machine for coal-based hydrogen. Critical to Phase III is a project partner able to coordinate with an OEM on the development, design, and manufacture of a machine for a specific project.

By FY 2015 (FOA Decision Point)

- Launch a new Transformational program, through an FOA for fossil fuel turbines that targets a 3,100 °F turbine inlet temperature.

By FY 2016

- Complete the component testing to support the design of a hydrogen turbine with a turbine inlet temperature 2,600–2,650 °F thereby demonstrating greater than 3 percentage point improvement in net plant efficiency for an IGCC with CCS and with a greater than 15 percent reduction in COE (improvements due to the turbine alone) (base and American Recovery and Reinvestment Act of 2009 [ARRA] project).[1]

1 Values relative to the current baseline IGCC and are consistent with a 4.3 percentage point improvement in efficiency and greater than 25 percent reduction in COE for an IGCC with CCS compared to the Turbines program 2003 baseline IGCC.

By FY 2017

- By 2017 down-select from three OEMs in Phase I to two OEMs in Phase II for component R&D and testing to demonstrate a fossil-fueled (coal-derived H_2, syngas, or natural gas) machine with a turbine inlet temperature of 3,100 °F.

By FY 2020 (part of the 2nd-Generation technology development, H_2 Turbine at 2,650 °F)

- OEMs pursue advanced 2nd-Generation hydrogen-fueled turbines on their own (2,650 °F turbine inlet temperature) in combined cycle operation for 2nd-Generation IGCC with CCS that can demonstrate efficiencies on the order of 40 percent (higher heating value) and a COE greater than 20 percent below today's IGCC with CCS. Likely support through a clean coal demonstration project. The advanced H_2 turbine contributes 4.3 percentage points to increased IGCC efficiency; total plant cost and COE are also significantly reduced. COE reductions due to the advanced turbine are 15 percent of the required 20 percent reduction.

By FY 2028

- Complete Phase II component testing in the Transformational hydrogen turbine project.
- FOA to award Phase III of the design and construction of a Transformational hydrogen turbine.

By FY 2031

- OEM takes over Transformational turbine construction with limited Government funding for an IGCC project with CCS.

By FY 2035

- Two-year demonstration period completed for a Transformational hydrogen turbine in an IGCC application with CCS.

4.2.4 TECHNOLOGY TIMELINE

Presented in Figure 4-1 is a nominal timeline for the development of both the 2nd-Generation (2,650 °F) and the Transformational (3,100 °F) hydrogen turbines for IGCC. Benefits are shown in the figure as a reduction in the cost of CO_2 per tonne relative to the cost to capture CO_2 baseline. FOAs would be required to initiate the Transformational technology in 2015 and to award the design and construction of the Transformational machine (Phase III) in 2028.

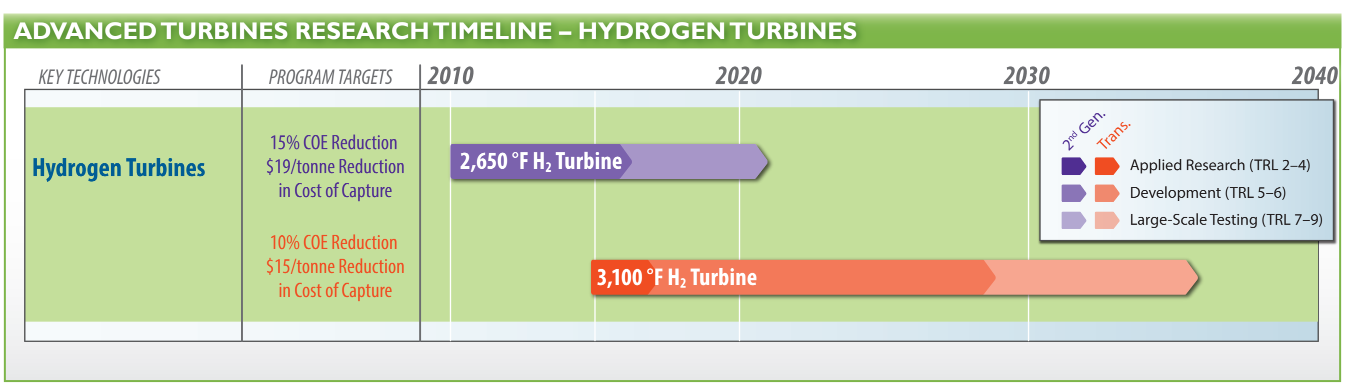

Figure 4-1. Hydrogen Turbines Development Timeline

4.2.5 RESEARCH FOCUS AREA BENEFITS

Turbine R&D provides significant benefit to the IGCC power system with CCS pathway. This is illustrated in Figure 4-2. In the 2nd-Generation case, the turbine provides well over 75 percent of the benefit required to reach the cost of CO_2 capture target of $40/tonne. At the same time achieving this goal also produces a 15 percent reduction in the COE. In the Transformational case, over 30 percent of the benefit required for the $10/tonne goal is targeted to be provided by the turbine.

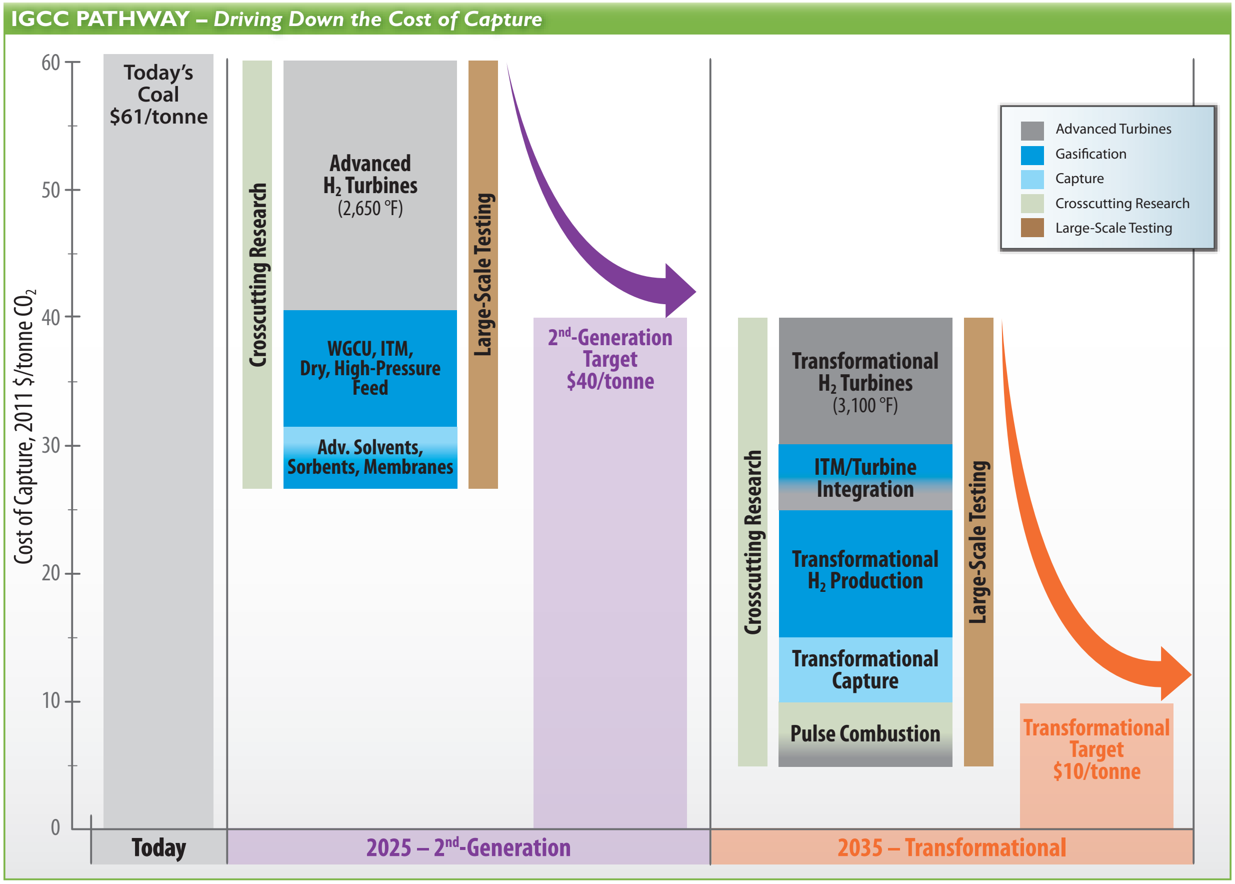

Figure 4-2. Targets for Technology Contributions to Overall CCRP Cost of Capture Goals—IGCC Pathway

4.2.6 BARRIERS/RISKS AND MITIGATION STRATEGIES

Table 4-1. **Issues/Barriers and Mitigation Strategies**

Issue	Barrier/Risk	Mitigation Strategy
Achieve emissions goal	High temperature H_2 turbines with high NO_x emissions	Burner design R&D
Achieve capital cost reduction performance target	Cost of turbine	Advanced manufacturing techniques
Achieve efficiency gain performance target	Performance of turbine does not meet expectations, turbine is not put into place	Turbine component testing and demonstration, collaboration with industry to ensure commercialization of developed technologies
Achieve all performance targets by 2030	Inadequate progress on cost and performance goals	Near-, mid-, and long-term R&D projects as well as laboratory, proof-of-concept, and pilot-scale projects to foster the commercialization of the technologies

4.3 SUPERCRITICAL CO_2 POWER CYCLES

4.3.1 BACKGROUND

The supercritical CO_2 power cycle operates in a manner similar to other turbine cycles, but it uses CO_2 as the working fluid in the turbomachinery. The cycle envisioned for the first coal-based application is a non-condensing closed-loop Brayton cycle with heat addition and rejection on either side of the expander. Generally, once the system is charged with CO_2, there is no addition or loss during operation. In this cycle, the CO_2 is heated indirectly from a heat source through a heat exchanger, not unlike the way steam would be heated in a conventional boiler. Energy is extracted from the CO_2 as it is expanded in the turbine. Remaining heat is extracted in one or more highly efficient heat recuperators to preheat the CO_2 going back to the main heat source. These recuperators help increase the overall efficiency of the cycle by limiting heat rejection from the cycle. Overall in this case, higher efficiency is realized since work is extracted through the turbomachinery at higher temperatures (there is no extraction of work at low condensing temperatures) and post-expansion heat is not dumped into a condenser (like a steam cycle).

The cycle is operated above the critical point of CO_2 so that it does not change phases (from liquid to gas), but rather undergoes drastic density changes over small ranges of temperature and pressure. This allows a large amount of energy to be extracted at high temperature from equipment that is relatively small in size. Supercritical CO_2 turbines can have a gas path diameter as small as a few inches compared to several feet for utility scale combustion turbines or steam turbines. The temperature profiles of typical heat sources like oxy-fueled pressurized fluidized bed combustors (PFBCs), are a better fit to those of the supercritical CO_2 working fluid than a typical steam cycle.

Fossil fuels, particularly coal, can provide an ideal heat source for supercritical CO_2 cycles. The open literature has shown that a supercritical CO_2 closed-loop cycle combined with a coal-fueled oxygen-blown PFBC has the potential to increase efficiency with a lower capital cost than a comparable supercritical steam-based Rankine cycle with the same turbine inlet temperature. Studies suggest that the supercritical CO_2 oxy-fuel PFBC system has the potential to significantly increase efficiency by 9 percentage points over other pulverized coal oxy-fuel combustion configurations with a 20 percent lower levelized COE and the potential for near 100 percent CO_2 capture. Water consumption and other emission profiles are also very attractive for this cycle. There are also opportunities to advance these performance numbers with higher firing temperatures made possible by advanced airfoil cooling technology.

The supercritical CO_2 cycle utilizes small efficient turbomachinery that is fuel and or heat source neutral and can make use of lower intensity heat sources. These factors make the cycle appealing to a wide range of applications and stakeholders. For instance the supercritical CO_2 cycle can be particularly attractive as a bottoming cycle for simple cycle gas turbines providing 15–20 additional percentage points improvement while retaining many of the desirable attributes of the simple cycle configuration. Other bottoming cycle applications will also be attractive. Due to the fuel and heat source neutrality, the cycle is also highly relevant to concentrated solar and nuclear applications, both areas of technology with a high level of DOE interest. DoD has also expressed a strong interest for naval propulsion and power due to the compactness and efficiency of this cycle, and the Naval Research Laboratory at Bettis has one of three supercritical CO_2 test loops in the United States. There are also opportunities for more advanced natural gas-based cycles that would involve direct heat addition thereby allowing higher firing temperatures and pressure without the use of heat exchangers. With advanced airfoil cooling these systems may have the potential for 65–75 percent fuel to bus bar efficiencies. This broad range of applications and configurations makes the market-based development and deployment of supercritical CO_2-based turbomachinery highly attractive.

4.3.2 TECHNICAL DISCUSSION

Initial studies[2] suggest that the technical issues for the supercritical CO_2 power cycle can be organized into three areas. These include (1) turbomachinery design, (2) heat exchanger design, and (3) materials of construction. A summary of these issues is provided in the following sections.

Turbomachinery Design—The high pressure, relatively high temperature, uncertainty of the CO_2 state near the critical point, and high power density create design challenges for the supercritical CO_2 turbomachinery. While excellent turbomachinery design tools are available, there is less experience with the closed loop supercritical CO_2 Brayton cycle design space of the envisioned size. While examples of turbomachinery that cover part of the design space (i.e., temperature, pressure, and power density) can be found, there is no single machine effectively working in the design space of interest. Collectively, the working fluid, temperature, and pressure will present considerable challenges in machine casing and airfoil design and performance during off-design conditions for the expanders. Design options and lower temperatures for the compressors will provide greater flexibility in material selection and machinery design and reduce the risk related to this technology challenge.

Heat Exchangers—Heat exchangers are key components of the supercritical CO_2 Brayton power cycle. Their performance in terms of pressure drop and heat transfer efficiency will directly impact the overall thermodynamic efficiency of the cycle. The operating conditions for these heat exchangers are challenging. New and innovative design concepts and solutions are required for these units to meet cost, weight, and volume limitations. Several heat exchanger design concepts have been evaluated and need to go through a rigorous optimization process.

Materials of Construction—The compatibility of materials in high-pressure and high-temperature carbon dioxide environments will impact hardware design, especially for turbine and heat exchanger components. Supercritical CO_2 is highly oxidative and expected to cause material degradation. Material degradation mechanisms are expected to include:

- Material loss and system contamination through oxidation and corrosion
- Oxygen embrittlement effects on the mechanical properties of materials
- Carburization effects on the mechanical properties of materials

The initial review of the literature suggests that the development of new materials will not be required for supercritical CO_2 power cycles operating up to 1,300 °F. Above this temperature, material degradation could be an issue. Clearly additional material assessments are required. A secondary concern is associated with the ability to manufacture production level materials for this power system in the United States.

The approach to this key technology is designed to mitigate these issues and minimize the risk associated with supercritical CO_2 cycles through the proposed technology R&D.

4.3.3 R&D APPROACH

To implement R&D on this Transformational technology, a new FOA would be required. The approach would be to bring together current Federal stakeholders through an NETL implemented FOA that would seek private sector cost-sharing partners to develop, test, and deploy a prototype commercial-scale supercritical CO_2 power cycle. The partnership would seek to share the Federal cost between DOE (Office of Fossil Energy, Office of Energy Efficiency and Renewable Energy, and Office of Nuclear Energy) and from DoD (through the Navy). The FOA would pursue a multiphase development program that would design and test supercritical CO_2 turbomachinery and allow for the manufacturing of commercial prototypes.

2 *Supercritical CO_2 Turbomachinery Technology Development for Power Plant Applications*, Contract: DE-AC07-03SF22307, June 2011, Prepared for: Leonardo Technologies, Inc., by Pratt & Whitney Rocketdyne, Inc., Canoga Park, California.

The FOA award will initiate a three-phase program in FY 2015. The first phase (Phase I) would require 12–18 months and result in an R&D implementation plan and a business development plan for supercritical CO_2 turbomachinery. Following the successful completion of Phase I and the continued interest by the Federal stakeholders, Phase II would begin in 2017. Phase II would focus on the design, manufacturing, and assembly of the supercritical CO_2 turbomachinery and on heat exchanger (recuperator) development, optimization, and construction. Phase II would also focus on a conceptual design of a test facility to assess the performance of the turbomachinery and heat exchangers. Phase III, issued through a 2024 FOA, would govern the fabrication of the test facility and testing of the turbomachinery and heat exchangers. Testing under Phase III would address any long-term operational, design, or material degradation issues. It is envisioned that application opportunities for this follow-on FOA could include multiple demonstration projects. Upon successful completion, this R&D approach will culminate in 2030 with the ability to design a family of commercial supercritical CO_2 turbomachinery products ready for deployment with fossil fuel, renewable, and nuclear heat sources.

By 2015

- Initiate and award an FOA to develop supercritical CO_2 turbomachinery (≈27 MWth) for advanced coal combustion and as a bottoming cycle for simple cycle gas turbine applications. These two different applications will have different temperature heat sources and as a result target different turbine inlet temperatures. The oxy-fuel PFBC will target a turbine inlet temperature of 1,500 °F and the simple cycle bottom cycle application will target a turbine inlet temperature on the order of 1,000 °F.

By 2017

- Initiate Phase II to develop supercritical CO_2 turbomachinery and heat exchangers.

By 2024

- Complete Phase II and the design and development of a 27-MWth supercritical CO_2 turbomachinery with recuperators to demonstrate, at a reduced scale, anticipated performance improvements in a coal-based oxy-fuel PFBC, on the order of 5 percentage points.
- Initiate Phase III through an FOA to design and build a 27-MWth test facility to test and evaluate Phase II turbomachinery and heat exchangers.

By 2027

- Complete testing of pre-commercial scale (27 MWth) turbomachinery and associated heat exchangers (recuporators).

4.3.4 TECHNOLOGY TIMELINE

Figure 4-3 illustrates the timeline for the development of supercritical CO_2 turbomachinery and recuperators needed to demonstrate an oxy-fuel PFBC with carbon capture. Once testing is complete (2027) of the pre-commercial scale hardware, a demonstration scale oxy-fuel PFBC (50 MWe) could be built with scaled up turbomachinery and heat exchangers to demonstrate the coal-based oxy-fuel PFBC concept.

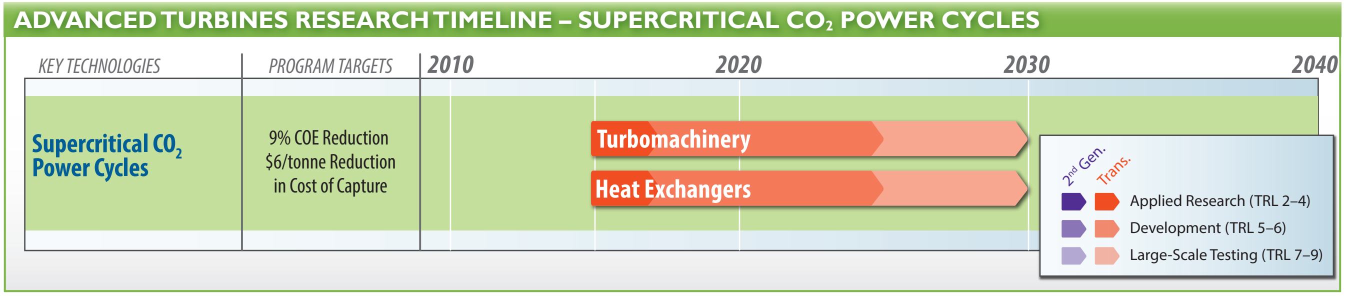

Figure 4-3. Supercritical CO_2 Power Cycles Development Timeline

4.3.5 RESEARCH FOCUS AREA BENEFITS

Supercritical CO_2 power cycles have the potential to benefit many applications due to the small size and high power density of the turbomachinery. For advanced coal power with CCS, the supercritical CO_2 cycle has the potential to add 4–6 percentage points to an oxy-fuel PFBC plant, as compared to the same plant with a steam cycle. This leads to 40 percent efficient (or higher) coal combustion with CCS. A supercritical CO_2 power cycle in this application is targeted to provide 26 percent of the benefit in reducing the 2nd-Generation cost of CO_2 ($40/tonne) to the Transformational goal (<$10/tonne).

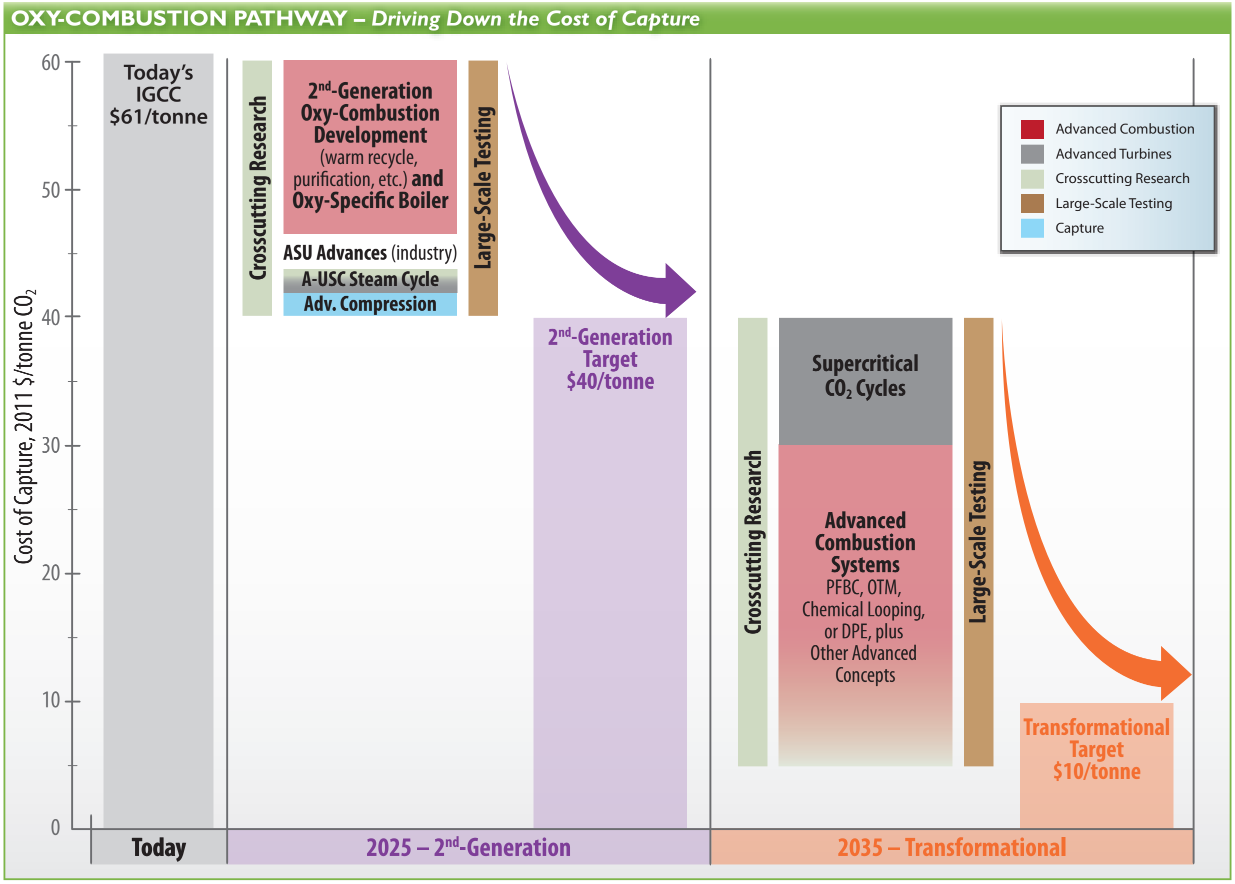

Figure 4-4. Targets for Technology Contributions to Overall CCRP Cost of Capture Goals—Oxy-Combustion Pathway

When a supercritical CO_2 power cycle is installed as a bottoming cycle for a simple cycle gas turbine, the plant efficiency can be increased by 15–20 percentage points, similar to that of a steam cycle, but with simple cycle attributes. The compactness of the turbines and the reduced water requirements will enable this cycle to be considered for heat recovery in many existing simple cycle operations.

4.3.6 BARRIERS/RISKS AND MITIGATION STRATEGIES

Presented in Table 4-2 are technical barriers and risks with the associated mitigation strategies for developing the supercritical CO_2 power cycle.

Table 4-2. **Issues/Barriers and Mitigation Strategies**

Issue	Barrier/Risk	Mitigation Strategy
Achieve heat exchanger design	Failure to meet efficiency cost, size, and weight goals for cycle recuperators	Rigorous R&D with industry leading OEMs and researchers to ensure optimized design
Achieve efficiency gain performance target	Power cycle is not implemented on a significant scale	Near-, mid-, and long-term R&D projects as well as laboratory, proof-of-concept, and pilot-scale projects to foster the commercialization of the technologies, as well as leveraging work with advanced combustion PFBC
Achieve turbomachinery prototype	Failure to deliver functional turbomachinery	Rigorous R&D with industry leading OEMs and researchers, engaging multiple Federal stakeholders

4.4 ADVANCED OXY-FUEL TURBINE

Oxy-fuel turbine-based technology offers a competitive power system with nearly 100 percent carbon capture and near-zero emissions of all other criteria pollutants. This system can operate with either coal-derived syngas or natural gas. Additionally, the oxy-fuel turbine concept has attributes that leverage opportunities in CO_2 enhanced oil and gas recovery market space by providing competitively priced CO_2, power and water while using fuels of little or no market value. This concept is being championed by Clean Energy Systems, Inc. and Siemens. The concept has received considerable investment by DOE-FE over the past 10 years.

4.4.1 BACKGROUND

Carbon dioxide EOR represents an attractive application for the oxy-fuel turbine power system. CO_2 EOR floods in the United States produce 280,000 barrels per day of crude oil, roughly 5 percent of domestic production. This EOR activity consumes 58 million metric tons of CO_2 per year and the potential for additional CO_2 use is much higher. A resource assessment developed by NETL estimates 60 billion barrels of economically recoverable oil resource via CO_2 EOR. The CO_2 demand to recover this 60 billion barrels is on the order of 17 billion metric tons. That estimate is for next-generation CO_2 EOR technology applied to onshore oil-bearing formations (above the oil/water transition zone) in the lower 48 States. If one considers a scenario where 17 billion metric tons of CO_2 is consumed over 60 years, the economic resource estimate represents a five-fold increase over the current demand for CO_2. The domestic CO_2 EOR industry is supply-limited and has been so for several years. Natural CO_2 sources are starting to peak and anthropogenic sources have a high cost structure. Prices paid for CO_2 are inching above the longstanding heuristic, 2 percent of crude oil price, but there remains a large gap between prices sought by potential suppliers of CO_2 and what oilfield operators are willing to pay ($70–$80 per metric ton of CO_2 versus $10–$35 per metric ton of CO_2). The Clean Energy Systems oxy-fuel turbine power system is a good match with a CO_2 EOR flood, producing power and CO_2, both of which are needed in a CO_2 flood and can be difficult to obtain at many locations. The mixture of associated gas and CO_2 that is produced along with the crude oil—and would normally be flashed off—can be consumed as fuel in the oxy-fuel turbine. The oxy-fuel turbine process can be configured to produce quality steam and nitrogen, both of which have the potential to be utilized in EOR fields for hybrid thermal/CO_2 and nitrogen/CO_2 tertiary recovery approaches.

Central to the DOE-FE ARRA investment in the Clean Energy Systems oxy-fuel turbine concept is the objective to demonstrate CO_2 utilization in industrial applications. The oxy-fuel turbine concept is benefiting from the market dynamics for CO_2 EOR and the unique attributes the system brings to this application. The oxy-fuel turbine power system will create new opportunities for domestic oil recovery through the use of CO_2. ARRA funds facilitate the strategy that industrial CO_2 use—while in and of itself a good thing—will also accelerate R&D for power generation with carbon capture. FE should now leverage this market-supported opportunity to further advance power-generation R&D in oxy-fuel turbine technology, EOR science and CO_2 use. Several key power-generation R&D issues can be addressed through an early demonstration of the oxy-fuel turbine concept for EOR. Addressing these issues will allow higher performance oxy-fuel turbine systems for power generation and EOR.

4.4.2 TECHNICAL DISCUSSION

There are a number of technology and design challenges to realizing the full benefits of the advanced oxy-fuel turbine. The primary areas of risk are the high turbine inlet temperature, high pressure, and the unique working fluid that consists mostly of steam and CO_2. This new turbine will also require new control systems and development of new cooling schemes, thermal barrier coatings (TBCs), and other coatings for this unique working fluid. It is also important that the oxy-fuel combustion process be accurately controlled so as to not waste oxygen or leave uncombusted fuel in the exhausted working fluid.

Oxy-Fuel Turbine Design and Operation—The drive gas in a normal gas-fired turbine consists of 70 to 80 percent nitrogen with minor fractions of oxygen, steam, and CO_2. In contrast, the drive gas produced for an oxy-fuel turbine contains 80 to 90 percent steam with most of the remainder being CO_2. A lack of extensive knowledge of this steam-CO_2 working fluid mixture at operating conditions creates design challenges for oxy-fuel turbines. There are also operation and control challenges associated with near-stoichiometric combustion, transient, and bypass operations, as well as new startup ramp rates for new materials. Conceptual development of cooling circuits for casings, rotors, and rotating airfoils will be required for satisfactory component life in the service environment. The ability to manufacture components with novel cooling features including highly complex three-dimensional cores will have to be developed and this requirement falls in line with currently active research under the hydrogen turbine pathway. The cost of exotic materials drives designers to minimize their use wherever possible.

Materials—In the proposed oxy-fuel cycles, the IP turbine operates at higher temperatures than both the high-pressure and low-pressure turbines, and therefore poses the most significant materials challenges. The near-term intermediate-pressure turbine inlet would operate at 2,460 °F, and the long-term intermediate-pressure turbine inlet would operate at 3,200 °F. These temperatures are much higher than conventional steam turbine inlet temperatures nominally between 900 and 1,000 °F, and conventional gas turbine inlet temperatures nominally between 2,400 and 2,600 °F. Operation under these conditions will require the development of new high-temperature sealing materials. Development of CO_2-tolerant materials and valve coatings will be needed for parts to survive for the appropriate service life.

Stoichiometric Oxy-Fuel Combustion—To optimize the oxy-fuel turbine system for either power or EOR applications it is desirable to achieve stoichiometric combustion conditions. There is little experience with fossil fuel combustion and pure oxygen and the equipment to hold stoichiometric conditions adds additional technical complexity. This issue will be further challenged when reheater combustion systems are added to achieve higher efficiencies. In this case the oxy-fuel combustion conditions will be diluted by high levels of steam and CO_2. Oxy-fuel combustion conditions will require new control strategies and a fundamental understanding of the oxy-fuel combustion process to optimize this system.

4.4.3 R&D APPROACH

The R&D approach proposed for advanced oxy-fuel turbine is designed to address the technical issues outlined previously. Successfully resolving these issues will reduce the risk associated with the development of oxy-fuel turbine technologies.

The potential exists for significant market pull and early deployment of the oxy-fuel turbine system for EOR applications. To ensure the success of future commercial deployments and to optimize this technology for fossil fuel-based power generation, a highly cost-shared multiple partner pre-commercial test campaign is envisioned. Since the project opportunity would consist of multiple stakeholders deploying a prototype system under near commercial conditions, the Government cost share would be low (≈25 percent).

The oxy-fuel turbine key technology R&D would focus on three objectives: (1) material testing for higher turbine inlet temperatures, (2) advanced oxy-fuel turbine design for power generation and EOR, and (3) oxy-fuel combustion development. These objectives would be pursued through a highly cost-shared demonstrations while allowing project partners to reduce commercial risk and optimize the integrated system for EOR. Materials testing would work to move current turbine inlet temperature from 2,000 °F (to be demonstrated in the current ARRA project) to 2,500 °F, evaluate turbine material life and assess material coatings in high temperature CO_2 and steam atmospheres. The current oxy-fuel turbine is based on a well-proven gas turbine modified for oxy-fuel turbine conditions and mechanical requirements. Future oxy-fuel turbines, whether they are based on existing platforms or move toward purpose-built machines, will benefit from advanced designs that allow better performance. Oxy-fuel combustion development would aim to improve the understanding of near-stoichiometric combustion to reduce the risk and difficulty associated with controls under this regime.

This R&D would include the use of the existing or new OFT-900 turbine in a fully integrated system including an air separation unit. An ideal test site for the oxy-fuel turbine system would be an EOR opportunity lacking a CO_2 source that would also produce a vitiated fuel, although other conventional fuels could be used. Contractually, it is proposed that this project be pursued through a modification of the existing ARRA contract by a determination of non-competitive financial assistance and build upon the accomplishments and progress of previous DOE-FE contracts.

By 2014

- Complete Clean Energy Systems ARRA project scope.
- Complete the determination of non-competitive financial assistance of the Clean Energy Systems ARRA project to include the design, construction and testing of a 1st-Generation OFT-900-based oxy-fuel turbine targeted for an EOR application. This determination of non-competitive financial assistance includes tasks on: (1) materials assessment for oxy-fuel turbine applications, (2) oxy-fuel combustion fundamentals and control, and (3) 2nd-Generation oxy-fuel turbine design. This entire effort would be highly cost-shared by industry (75/25, industry/Government).

By 2016

- Initiate funding on 1st-Generation oxy-fuel turbine project for clean power and EOR application, oxy-fuel turbine material development, and oxy-fuel combustion fundamentals and control.

By 2021

- Initiate operation of 1st-Generation oxy-fuel turbine system in an EOR application.
- Complete assessments on oxy-fuel materials assessment and combustion.
- Initiate design of a 2nd-Generation oxy-fuel turbine.

By 2024

- Complete Government-supported EOR and clean power demonstration.
- Industry-sponsored 2nd-Generation project begins with no Government cost share. Government support 2nd-Generation turbine design work feeds into this project for operation in a 2031–2034 timeframe.

4.4.4 TECHNOLOGY TIMELINE

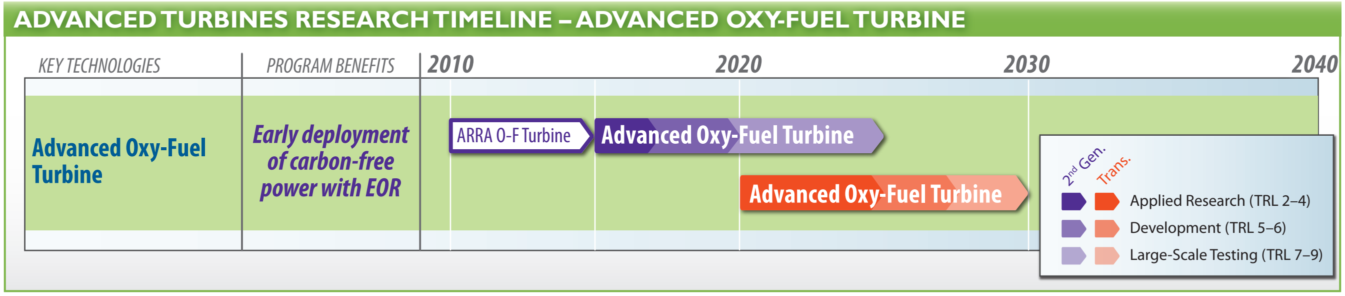

Figure 4-5. Advanced Oxy-Fuel Turbine Development Timeline

4.4.5 RESEARCH FOCUS AREA BENEFITS

This research area has overall benefits of developing and demonstrating oxy-fuel turbine technology for clean power and EOR applications that would otherwise be stranded due to the lack of CO_2. The research with in this area will focus on three primary areas including: (1) developing a new material set for a higher temperature 2nd-Generation oxy-fuel turbine system, (2) advancing oxy-fuel combustion understanding and control systems for more advanced and higher temperature combustion systems suitable for 2nd-Generation oxy-fuel turbines, and (3) supporting the demonstration of this technology in an EOR application. By conducting this early demonstration, the oxy-fuel turbine-based system will be advanced, further promoting its use as a clean fossil fuel power source with only pure CO_2 as the exhaust.

4.4.6 BARRIERS/RISKS AND MITIGATION STRATEGIES

Presented below is a table outlining potential issues, the associated risk, and mitigation strategies for each risk. Fundamentally, these issues center on determining and/or developing the appropriate material set for an oxy-fuel turbine and understanding and controlling stoichiometric oxy-fuel combustion. Resolving these issues will allow for the successful design of an optimized oxy-fuel turbine.

Table 4-3. **Issues/Barriers and Mitigation Strategies**

Issue	Barrier/Risk	Mitigation Strategy
Accelerated material degradation in a high-temperature steam and CO_2 environment	Premature turbine failure and forced operation at reduced temperature to avoid material failure	Assess temperature limitations for prescribed material set and keep temperature below failure threshold; implement material assessment program to determine optimum material set
Limitation on high temperature operation for working fluid (steam and CO_2)	Lower operating temperature leads to reduced system efficiency and reduced plant performance	Develop/determine improved material set for turbine allowing higher operating temperature
Inability to maintain stoichiometric oxy-fuel combustion conditions	Too much oxygen effects plant performance by wasting energy producing oxygen, effects CO_2 separation and purity; too much fuel effects plant performance by wasting fuel and effects CO_2 purity	Develop better combustion control system and fundamental understanding of oxy-fuel combustion phenomena
Oxy-fuel turbine design flaw	Premature turbine failure and/or plant shutdown	Assess turbine performance during startup and shake down; identify potential issues and assess time to failure; develop design improvements

4.5 ADVANCED STEAM TURBINES

Steam turbines represent the vast majority of electrical production machines in the world and will continue in this position for many decades to come. Because of their magnitude in the electrical market place, advancing steam turbine performance has the ability to make tremendous beneficial impacts. Improvements in thermal efficiency can benefit energy sustainability and the environment. Specifically, higher thermal efficiencies reduce fuel consumption, CO_2 emissions, and cooling water requirements per megawatt hour. Finally, by reducing the amount of flue gas for each megawatt produced, higher thermal efficiency can reduce the cost of emission controls.

4.5.1 BACKGROUND

Over the past 100 years, the average thermal efficiency of coal-fueled, steam-turbine-based power plants in the United States has increased from the mid-teens to near 34 percent. Over the course of this time, these performance improvements were achieved in part by advancing existing turbine designs and increases in steam conditions. In 1960, The Eddystone 1 plant was commissioned with a rating of 325 MW and inlet pressure and temperature of 5,000 psi and 1,200 °F. Eddystone's best case thermal efficiency was near 40 percent. Since 1960, state-of-the-art steam conditions have reduced while plant and turbine technologies have improved to yield new unit thermal efficiencies of 48 percent for turbines rated up to 800 MW. Based on the trend in steam turbine technology over the past 50 years, we find ourselves at the point where the next step needs to be identified and developed.

4.5.2 TECHNICAL DISCUSSION

A logical next step for steam turbine technology is an increase in the thermal operating conditions. Current, state-of-the-art technology operates at thermal conditions as high as 3,800 psi and 1,180 °F, known as ultra-supercritical (USC). However, over the past several years, there have been developments in the United States—as well as in other places around the world—to develop boiler tube materials that are capable of higher conditions, up to 5,000 psi and 1,400 °F. There is now a need to design a steam turbine that is capable of leveraging these advances.

Based on preliminary analysis, a steam turbine cycle operating at the higher conditions referenced previously would be capable of thermal efficiencies in the 55–60 percent range. There is a lot to be understood about how to design, manufacture, and operate a steam turbine at such advanced steam conditions. There are multiple architecture and technology developments, and/or inventions needed to implement a turbine at these conditions, as well as significant component testing and evaluations to prove the technologies and reduce any risks.

Development of an A-USC steam turbine requires addressing a number of technology and design challenges. Some of these challenges involve application of new, high-temperature materials and other challenges involve extension of current technologies into new temperature and pressure regimes. Specific focus areas include materials, technology for expansion and clearances control, designs for rotor dynamics, designs for rotating parts, steam valve development, and design of high-pressure casings.

Materials—Steam temperatures above 1,150 °F require the application of new material families. These materials will be utilized in massive equipment sizes and expected to maintain their integrity for extended periods of time in extreme operating environments. The DOE A-USC materials program has investigated several superalloys for use in the major components, such as rotors and shells. Building off of this important program, steam turbine components can now be designed that leverage these material developments.

Technologies for Expansion and Clearances—Large A-USC steam turbines are expected to consist of up to five turbine sections and be attached to a generator at the low-pressure end. Technology advancements in steam turbine architecture, clearance prediction, leakage management, monitoring, and control will be necessary to minimize the efficiency impact of the large thermal expansions between rotating and stationary airfoils and seals.

Design for Rotor Dynamics—Rotor dynamic behavior is strongly impacted by stage pressure. For A-USC steam conditions, it will be necessary to clearly understand the impact of elevated steam conditions (primarily pressure) on rotor dynamic behavior. Historical experience at the lower USC conditions have shown this to be critical design area and current thinking will have to be reevaluated.

Design for Rotating Parts—Like a modern day aircraft engine or large industrial gas turbine rotor, an advanced A-USC steam turbine rotor will require a finite amount of nickel-based components in the highest temperature region. A-USC development activities will include investigation of the unique corrosive and oxidation characteristics of selected superalloys exposed long term to advanced steam conditions. Fatigue and rupture lives of all rotating components will be calculated and assessed on the basis of prevailing industry expectations.

Steam Valve Development—The valves associated with the safe operation and control of an A-USC steam turbine are a critical design element. Materials for the casing, stems, and bushings will be similar to those of the turbine section shells and rotors. Control valves with excellent throttling characteristics are important for A-USC power-plant operational flexibility and reliability. Higher pressures will drive the need for the design of operating mechanisms of large physical size.

Design of High-Pressure Casings—Like the steam valve bodies, high-pressure casings will be designed with careful consideration of boiler and pressure vessel code safety criteria. Like the turbine rotor, a finite quantity of nickel-based superalloy in A-USC applications will be required, both for casings and bolted joints. A-USC development efforts will include fabrication methods for pressure bearing casings.

It is anticipated that as the previously described technology is developed, there will be opportunity to leverage the concepts into adjacent markets. The primary objective is to develop a steam turbine design capable of operating at A-USC conditions. Once this objective is achieved, the steam turbine can be utilized in a cycle with any heat source. These include a coal-fired boiler, future gas turbine combined cycle, or in an IGCC configuration.

4.5.3 R&D APPROACH

Advanced steam turbine R&D will be carried out through a three-phase program. The initial phase will include cycle optimization studies that would target initial steam conditions, variations in regenerative Rankine cycle, and ranges of megawatt output. From these thermodynamic studies, it will be possible to identify critical technology needs and better understand the interaction of these advance steam conditions on the steam turbine architecture. The second phase would be a detailed effort focused on the critical technologies, experimental evaluation of components, and potentially a subscale demonstration unit. Finally, the last phase would be focused on building a prototype commercial scale unit with planned operation for a period of time as called for in the development plan.

By 2015

- Initiate advanced steam turbine FOA for 4,000–5,500 psia, 1,300–1,400 °F inlet conditions (Phase I).

By 2016

- End of Phase I—establish the approach to realizing performance improvements in advanced steam turbines (anticipated 10 percentage points improvement on current steam cycle) and show how this advanced turbine will support system-level performance improvements for coal-based combustion, IGCC, and natural gas combined cycle.

By 2020

- Complete Phase II—component design, development, and testing to establish technology improvements that allow performance benefits established in Phase I to be realized.
- Initiate Phase III—design and manufacturing of a commercial prototype advanced steam turbine.

By 2023

- Complete Phase III—design and manufacturing of a commercial advanced steam turbine (5,500 psia/1,400 °F) for deployment and operation in a coal-based power system.

By 2025

- Initiate testing and operation of a commercial prototype advanced steam turbine.

By 2026

- Complete 1 year of operation of a commercial prototype advanced steam turbine.

4.5.4 TECHNOLOGY TIMELINE

Presented Figure 4-6 is a nominal timeline for the development of advanced steam turbines.

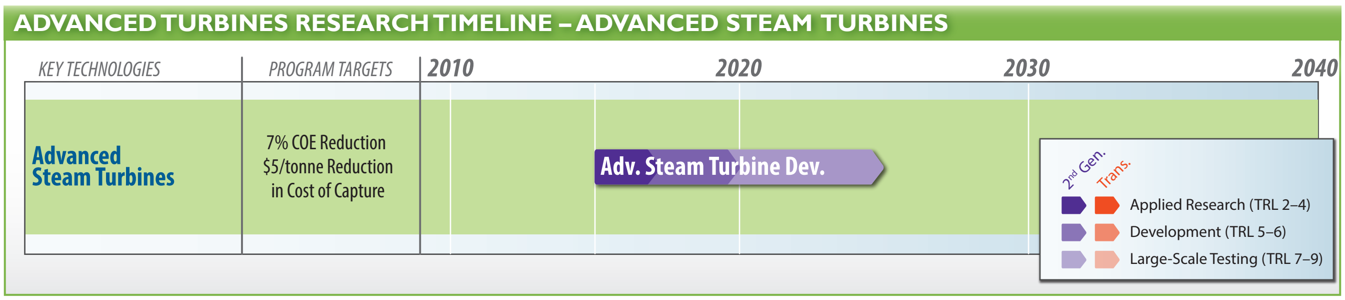

Figure 4-6. Advanced Steam Turbines Development Timeline

4.5.5 RESEARCH FOCUS AREA BENEFITS

The development of an A-USC steam turbine will have wide-reaching benefits across the power-generation sector. The steam turbine improvements are fuel-neutral and will be applicable to all steam turbine installations, regardless of fuel. The expected improvement in thermal efficiency of 10 percent will have the largest affect on boiler-type plants, including PC boilers, with a plant efficiency improvement of 2–3 percentage points. A-USC steam turbines in bottoming cycle configurations—such as an natural gas combined cycle or IGCC—will improve plant efficiency by ≈0.5 percentage points. An A-USC steam turbine in a PC plant with CCS application provides 17 percent of the benefit in reducing the 1st-Generation cost of CO_2 ($60/tonne) to the 2nd-Generation goal ($40/tonne).

4.5.6 BARRIERS/RISKS AND MITIGATION STRATEGIES

Presented below is a table outlining potential issues, the associated risk, and mitigation strategies for each risk.

Table 4-4. **Issues/Barriers and Mitigation Strategies**

Issue	Barrier/Risk	Mitigation Strategy
Materials	Lack of or slow development of materials	Leverage work from DOE USC program
Technologies for expansion and clearances	Large thermal expansions between rotating and stationary components lead to large leak rates that reduce efficiency and performance	Leverage similar work from leak management in hydrogen turbine program, utilizing industry leading OEMs and researchers
Design for rotating parts	Elevated steam conditions lead to increased airfoil degradation resulting in reduced service life and increased costs	Rigorous R&D with industry leading OEMs and researchers to ensure robust design development
Steam valve development	Valves that are prohibitively expensive or lack of properly sized valves available for operation at higher steam conditions	Leverage work from DOE USC program for material selection/development, rigorous R&D for materials and final design testing, collaboration with industry to ensure commercialization of developed designs
Design of high-pressure casings	Casing materials are too expensive, or perform poorly, leading to catastrophic failure	Leverage work from DOE USC program for material selection/development

Fundamentally, these issues center on determining and/or developing the appropriate material set and designs for an advanced ultra-supercritical steam turbine. Resolving these issues will allow for the successful design of an optimized ultra-supercritical steam turbine for fossil-fuel applications.

CHAPTER 5: IMPLEMENTATION AND COORDINATION PLAN

5.1 COORDINATION WITH OTHER ELEMENTS

The R&D approach that has been utilized historically for the successful development of advanced turbine technologies will continue to be employed through the development of the technologies in these pathways. Challenges in turbine technology development generally fall into the established research areas of combustion, aero/thermal/mechanical design (including cooling and leakage), and materials. Development of supercritical CO_2 cycles will require test loop design and construction to increase operational understanding and move toward commercial acceptance.

Turbine stakeholders in the United States—from academia and industry—are heavily invested in the turbine development process. The established relationships with DOE through the UTSR program, and FOA process will feed well into bringing the proposed key technologies to fruition if adequate funding is made available.

5.2 NEXT STEPS

The future of the Advanced Turbines program is uncertain in the current funding climate. Industry and academia are prepared to take on additional R&D challenges, but reductions in funding are poised to jeopardize the extent to which additional projects will be implemented. The current hydrogen turbines projects are set to end in 2015. In order for projects already in place to continue work or fund new work to move technologies toward demonstrations, it will be necessary to implement FOAs in FY 2014 and FY 2015 for:

- Advanced hydrogen turbine development
- Supercritical CO_2 power cycles
- Advanced steam cycles

It is recommended that the Clean Energy Systems ARRA project be held open (since work is expected to be completed in 2013) and that a determination of non-competitive financial assistance be implemented in 2014 (or 2013) to extend the work under current contract. This extension will support the intent of the ARRA project by demonstrating the 1st-Generation oxy-fuel turbine system for clean power.

As currently constituted, the Advanced Turbines program has adopted a comprehensive, multipronged R&D approach. R&D on a portfolio of technologies is being pursued along multiple paths to enhance the probability of success of research efforts that are operating at the boundaries of current scientific understanding. The R&D covers a wide scale, integrating advances and lessons learned from fundamental research, technology development, and demonstration-scale testing. The success of this effort will enable cost-effective implementation of advanced power-generation technologies.

Over the past several years, funding support for DOE's Advanced Turbines program has been reduced from historical levels in the \$30 million range to the FY 2013 request of ≈\$12,500,000. At this low level, Transformational key technologies will not be pursued and it is likely that support for one of the two U.S. DOE turbine development partners—whom have contributed significant private-sector funds to the efforts—will be terminated. This will result in the DOE discontinuing research on advanced concepts and not pursuing others that would have significant national benefit.

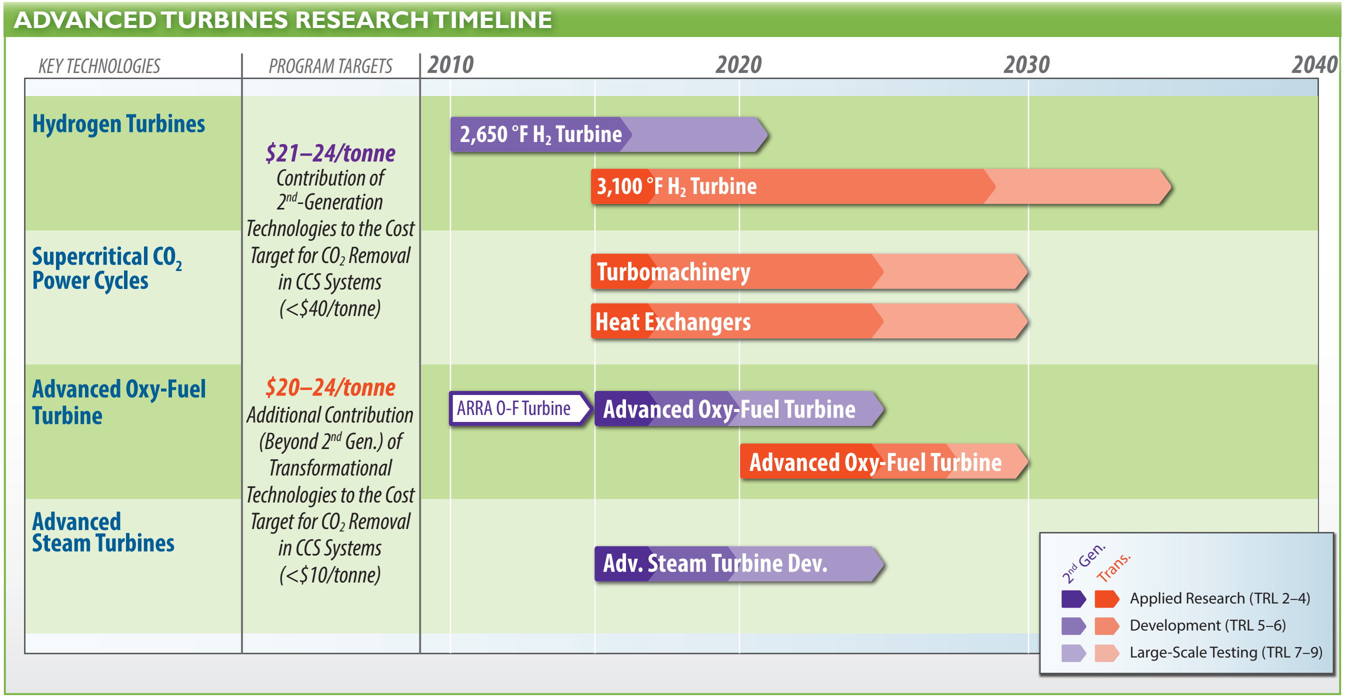

Figure 5-1. Advanced Turbines RD&D Roadmap

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APPENDIX A: DOE-FE TECHNOLOGY READINESS LEVELS

Table A-1. **Definitions of Technology Readiness Levels**

TRL	DOE-FE Definition	DOE-FE Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants.
4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in a laboratory and testing with a range of simulants.
5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory-scale system in a simulated environment with a range of simulants.
6	Engineering/pilot scale, similar (prototypical) system demonstrated in a relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up from a TRL 5. Examples include testing an engineering scale prototype system with a range of simulants. TRL 6 begins true engineering development of the technology as an operational system.
7	System prototype demonstrated in a plant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants. Final design is virtually complete.
8	Actual system completed and qualified through test and demonstration in a plant environment	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system within a plant/CCS operation.
9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of plant/CCS operations.

APPENDIX B: ACTIVE ADVANCED TURBINES PROJECTS

(AS OF OCTOBER 2012)

Table B-1. **Advanced Turbines Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
Key Technology—H_2 Turbines				
NT42644	Siemens Energy, Inc.	Advanced Hydrogen Turbine Development	4–5	Develop advanced hydrogen-fueled-turbine machinery to increase efficiency and performance of IGCC systems by constructing and testing improved hydrogen combustion components, material systems, sensors, and manufacturing processes for advanced airfoil designs.
NT42643	General Electric Company	Advanced Hydrogen Turbine Development	5	Develop advanced hydrogen-fueled-turbine machinery to increase efficiency and performance of IGCC systems by constructing and testing improved hydrogen combustion components, materials, sensors, and airfoil designs.
Key Technology—Oxy-Fuel Turbines for EOR and Power				
NT42645	Clean Energy Systems, Inc.	Oxy-Fuel Turbomachinery Development for Energy-Intensive Industrial Applications	4	Develop novel oxy-fuel turbine technologies to demonstrate feasibility of industrial power generation with >99% CO_2 capture by modifying a commercial Siemens SGT-900 gas turbine for oxy-fuel operation and conducting validation tests.
Key Technology—Combustion Systems				
7-678402	Lawrence Berkeley National Laboratory	Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants	4–5	Adapt low-swirl combustion technology for use with hydrogen fuels to meet ultralow NO_x emission targets for IGCC systems by developing a conceptual low-swirl-injector prototype and conducting fundamental laboratory studies on premixed turbulent flame speeds.
NT0005054	Pennsylvania State University	Combustion Dynamics in Multinozzle Combustors Operating on High-Hydrogen Fuels	3	Develop physics-based flame-response models for the design of high-hydrogen combustors to improve the performance and reduce emissions from hydrogen combustion by utilizing research facilities to study combustion dynamics in multinozzle flame configurations.
FE0000752	Pennsylvania State University	An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High-Hydrogen-Content Fuels	3	Advance understanding of the effects of water, CO_2, and other contaminants on ignition and combustion of high-hydrogen-content (HHC) fuels to develop guidelines for composition limits and operating characteristics that will improve the design and operability of hydrogen combustors by conducting laboratory experiments and chemical kinetic modeling.
FE0004679	Texas Engineering Experiment Station	Turbulent Flame Speeds and NO_x Kinetics of High-Hydrogen-Content Fuels with Contaminants and High Dilution Levels	3	Demonstrate validity of a comprehensive kinetics model to predict NO_x formation, flame speeds, and ignition behavior of HHC fuels for IGCC by conducting laboratory experiments in flame-speed and shock-tube facilities to improve existing kinetics models.
FE0007045	University of California, Irvine	Development of Criteria for Flameholding Tendencies Within Premixer Passages for High-Hydrogen-Content Fuels	3	Evaluate flameholding tendencies to develop design guides that will improve HHC fuel combustor design by conducting high-temperature, high-pressure experiments that simulate conditions in industrial-scale turbines.
FE0007099	Purdue University	Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High-Data-Rate Laser Diagnostic Investigation	3	Develop a validation database for comparison with detailed numerical models to improve the operability of HHC combustors by conducting experiments using advanced laser diagnostics to probe the flow fields in a high-pressure gas turbine combustion facility.
Key Technology—Materials and Material Architectures				
FEAA070	Oak Ridge National Laboratory	Material Issues in IGCC/Hydrogen Turbines	3	Improve understanding of material issues in HHC-fueled turbines to reduce degradation and increase performance by studying the effect of water vapor contents during cycling, quantifying the benefit of adding doping elements to superalloys and bond coats, and characterizing microstructures of bond coat systems.
FE0004734	Louisiana State University System	Computational Design and Experimental Validation of New Thermal Barrier Systems	3	Develop a high-performance thermal barrier coating to improve the performance of HHC-fueled turbines by using high-performance computing simulations of an ab-initio molecular-dynamics-based design tool to screen and identify TBC systems with desired physical properties.
FE0004727	University of California, Irvine	Mechanisms Underpinning Degradation of Protective Oxides and Thermal-Barrier Coating Systems in HHC-Fueled Turbines	3	Evaluate the potential impacts of coal-derived syngas and HHC fuels on the degradation of turbine hot-section components to address turbine materials stability concerns by conducting tests in simulated syngas and HHC environments to evaluate materials evolution and degradation mechanisms.

Table B-1. **Advanced Turbines Projects**

Agreement Number	Performer	Project Title	TRL	Relevancy Statement
FE0004771	The Research Foundation of State University of New York	Advanced Thermal Barrier Coatings for Operation in High-Hydrogen-Content-Fueled Gas Turbines	3	Improve science-based understanding of depositing bond coats and TBCs to create a pathway for reliable IGCC coating performance and provide new insight by conducting a systematic evaluation of multilayer coatings on nickel superalloys to determine properties, understand degradation mechanisms, and ultimately optimize performance and durability.
FE0000765	University of Texas at El Paso	Novel Hafnia-Based Nanostructured Thermal-Barrier Coatings for Advanced Hydrogen Turbine Technology	3	Develop hafnium-based TBCs to improve performance in IGCC by conducting experiments to optimize deposition parameters and chemical compositions, characterize microstructural, thermal, chemical, and physical properties, and ultimately quantify performance benefits.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 3: Coatings and Materials Development	3	Develop integrated composite thermal-barrier coating systems to permit future land-based gas turbine power-generation engine operation at extreme temperatures (i.e., >1,400 °C) through development and manufacture of advanced and/or reduced-cost materials and through conduct of laboratory-scale, high- and/or extreme-temperature testing at near-commercial conditions to assess material performance.
Key Technology—Aerodynamics and Heat Transfer				
AL05205018	Ames Laboratory	Analysis of Gas Turbine Performance	3–4	Advance turbine cooling strategies to improve cooling performance in industrial turbines by developing computational fluid dynamics (CFD)-based analysis tools, examining the basis of experimental methods used to valid CFD analysis tools, and applying said tools to development of turbine technologies.
FE0006696	Florida Turbine Technologies, Inc.	Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines	3–4	Demonstrate Spar-Shell™ turbine airfoil technology to improve advanced gas turbine and IGCC system efficiency by designing, analyzing, fabricating, assembling, installating, and testing prototype airfoils to validate performance in a commercial turbine application.
FE0005540	University of Texas at Austin	Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls	3	Analyze shallow-trench film-cooling configurations and effects of deposition on endwall cooling configurations to improve the durability of turbine components by conducting wind-tunnel experiments that simulate turbine environments.
FE0004588	University of North Dakota	Environmental Considerations and Cooling Strategies for Vane Leading Edges in a Syngas Environment	3	Explore technology opportunities to improve the reliability of HHC fuels for gas turbines by analyzing the effects of free-stream turbulence level, geometry, deposition, and cooling on the heat load experienced by turbine vane leading edges.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 2: Aerothermal and Heat Transfer	3	Develop advanced-internal-airfoil heat-transfer and film-cooling designs to permit higher temperature gas-turbine operation and therefore higher system operation efficiency by performing CFD modeling and conducting fundamental laboratory bench-scale testing as well as high-temperature testing at near-commercial conditions using coupon architectures.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 4: Design Integration and Testing	3	Evaluate advanced ceramic matrix composites and oxide-dispersion-strengthened matrices for potential use in advanced land-based gas turbine engines and develop high-temperature validated laboratory bench-scale testing capabilities to assess the performance of these material systems as well as advanced internal-heat-transfer and film-cooling designs at near-commercial engine operating conditions.
2012.03.02	National Energy Technology Laboratory	NETL Energy Systems Dynamics Activities, Turbine Thermal Management Field Work Proposal—Task 5: Secondary Flow Rotating Rig	3	Design and construct a world-class secondary-flow rotating test facility that is focused on demonstrating improved rotaing-blade-platform sealing which ultimately reduces fuel burn and improves overall power-generation plant efficiencies through operation of the 1.5-staged turbine at conditions replicating modern gas-turbine engines.

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APPENDIX C: ADMINISTRATION AND DOE PRIORITIES, MISSION, GOALS, AND TARGETS

ADMINISTRATION PRIORITIES

Presidential Goal—Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies

PRESIDENTIAL ENERGY TARGETS

- Reduce energy-related greenhouse gas emissions by 17 percent by 2020 and 83 percent by 2050, from a 2005 baseline.
- By 2035, 80 percent of America's electricity will come from clean energy sources.

DOE STRATEGIC PLAN—HIERARCHY OF RELEVANT MISSION, GOALS AND TARGETS

SECRETARIAL PRIORITIES

- ***Clean, Secure Energy:*** Develop and deploy clean, safe, low-carbon energy supplies.
- ***Climate Change:*** Provide science and technology inputs needed for global climate change negotiations; develop and deploy technology solutions domestically and global.

MISSION

The mission of the Department of Energy is to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

GOALS

- Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.
- Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity, with clear leadership in strategic areas.

TARGETS

- Sustain a world leading technical work force
- Deploy the technologies we have
  - Demonstrate and deploy clean energy technologies
  - Enable prudent development of our natural resources
- Discover the new solutions the nation needs
  - Accelerate energy innovation through pre-competitive research and development
  - Facilitate technology transfer to industry
  - Establish technology test beds and demonstrations
  - Leverage partnerships to expand our impact
- Deliver new technologies to advance our mission
  - Lead computational sciences and high-performance computing

- Use Energy Frontier Research Centers where key scientific barriers to energy breakthroughs have been identified and we believe we can clear these roadblocks faster by linking together small groups of researchers across departments, schools and institutions
- Use ARPA-E, a new funding organization within the Department, to hunt for new technologies rather than the creation of new scientific knowledge or the incremental improvement of existing technologies

FOSSIL ENERGY RESEARCH AND DEVELOPMENT

MISSION

The mission of the Fossil Energy Research and Development program creates public benefits by increasing U.S. energy independence and enhancing economic and environmental security. The program carries out three primary activities: (1) managing and performing energy-related research that reduces market barriers to the environmentally sound use of fossil fuels; (2) partnering with industry and others to advance fossil energy technologies toward commercialization; and (3) supporting the development of information and policy options that benefit the public.

CLEAN COAL RESEARCH PROGRAM

MISSION

The CCRP will ensure the availability of near-zero atmospheric emissions, abundant, affordable, domestic energy to fuel economic prosperity, increase energy independence, and enhance environmental quality.

STRATEGIC GOAL

Catalyze the timely, material, and efficient transformation of the nation's energy systems and secure U.S. leadership in clean energy technologies.

STRATEGIC OBJECTIVES

- Deploy the technologies we have
- Discover the new solutions the nation needs
- Deliver new technologies to advance our mission

STRATEGY

- Accelerate energy innovation through pre-competitive research and development
- Demonstrate and deploy clean energy technologies
- Facilitate technology transfer to industry
- Establish technology test beds and demonstrations
- Leverage partnerships to expand our impact

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ABBREVIATIONS

AES	Advanced Energy Systems
ARRA	American Recovery and Reinvestment Act of 2009
ASU	air separation unit
A-USC	advanced ultra-supercritical
Btu	British thermal unit
°C	degrees Celsius
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CFD	computational fluid dynamics
CO_2	carbon dioxide
COE	cost of electricity
DoD	Department of Defense
DOE	Department of Energy
EIA	Energy Information Administration
EOR	enhanced oil recovery
°F	degrees Fahrenheit
FE	Office of Fossil Energy
FOA	funding opportunity announcement
FY	fiscal year
GW	gigawatt
H_2	hydrogen
HHC	high-hydrogen content
HHV	higher heating value
IGCC	integrated gasification combined cycle
MW	megawatt
MWh	megawatt hour
MWth	megawatt thermal
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
NO_x	nitrogen oxides
O&M	operating and maintenance
OEM	original equipment manufacturer
OFT	oxy-fuel turbine
PC	pulverized coal
PFBC	pressurized fluidized bed combustor
psi	pounds per square inch
psia	pounds per square inch absolute
R&D	research and development
RD&D	research, development, and demonstration
syngas	synthesis gas
T&S	transport and storage
TBC	thermal barrier coating
TRL	Technology Readiness Level
USC	ultra-supercritical
UTSR	University Turbine Systems Research

FOR MORE INFORMATION

National Energy Technology Laboratory
http://www.netl.doe.gov/technologies/coalpower

U.S. Department of Energy, Office of Fossil Energy
http://www.fossil.energy.gov/programs/powersystems

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